Géographie physique et Quaternaire

lsotopic and Palynological Records of the Late Pleistocene in Eastern Canada and Adjacent Ocean Basins

Stratigraphie isotopique et palynostratigraphie du Pléistocène supérieur dans l’est du Canada et les bassins océaniques adjacents

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Volume 43, numéro 3, 1989

Le VI[e] Congrès de l’Association québécoise pour l’étude du Quaternaire

URI : https://id.erudit.org/iderudit/032783ar
DOI : https://doi.org/10.7202/032783ar

Aller au sommaire du numéro

Éditeur(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (imprimé)
1492-143X (numérique)

Citer cet article

Hillaire-Marcel, C. & de Vernal, A. (1989). lsotopic and Palynological Records of the Late Pleistocene in Eastern Canada and Adjacent Ocean Basins. *Géographie physique et Quaternaire*, *43*(3), 263–290. https://doi.org/10.7202/032783ar

Résumé de l'article

La comparaison des enregistrements isotopiques et palynologiques des mers de Baffin et du Labrador avec ceux que fournissent la palynologie et la chronologie U/Th de séquences continentales, autorise l'établissement d'un schéma climatostratigraphique régional représentatif des fluctuations climatiques du Pleistocene supérieur dans l'est du Canada. Pendant l'optimum climatique du stade isotopique 5e, des conditions plus chaudes que celles de l'Actuel ont caractérisé les milieux océanique et continental. La transition 5e 5d est marquée par une augmentation brutale des teneurs en 180 des foraminifères dans les mers de Baffin et du Labrador, en réponse à la formation de calottes glaciaires dans les milieux circumpolaires du nord-est du Canada. Pendant les stades 5d à 5a, le secteur arctique connut des conditions glaciaires, alors que dans la mer du Labrador et les provinces atlantiques des conditions subarctiques à tempérées fraîches persistèrent. Un bref (<104ans) stade 4 se distingue par une augmentation notable des teneurs en 180 dans les séquences océaniques: il correspondrait au développement méridional de l'Inlandsis laurentidien pendant le Wisconsinien inférieur, par ailleurs daté d'environ 80,000 ans dans les basses terres du Saint-Laurent. Rien ne permet cependant de démontrer que des conditions pleinement glaciaires existaient aussi dans les provinces atlantiques. Le stade 3 (Wisconsinien moyen) est caractérisé par des fluctuations des teneurs en 180 des foraminifères indiquant des transits épisodiques d'eau de fonte dans les mers du Labrador et de Baffin. En dépit d'un important volume de glace s'étendant sur l'est du Canada, certaines régions connurent des conditions de marge glaciaire: dans les provinces atlantiques, en particulier à l'île du Cap-Breton. Ia palynostratigraphie révèle l'existence d'un climat subarctique à hémiarctique; au pied des Appalaches au Québec, le lac proglaciaire Gayhurst s'est formé vers 46,000 ans avant l'Actuel. Au cours du stade 2 (Wisconsinien supérieur), l'inlandsis laurentidien a atteint son volume maximal alors que des calottes satellites se sont formées dans les provinces atlantiques. Dans les carottes océaniques, des fortes teneurs en 180 témoignent des conditions pléniglaciaires du stade 2, bien que des valeurs relativement faibles dans le secteur ouest de la mer du Labrador indiquent des apports d'eau de fonte discrets mais quasi continus. Une phase précoce de fonte glaciaire de la marge nord-est de l'inlandsis se traduit par une baisse des teneurs en 180 peu après 16,700BP. Le retrait final des glaces laurentidiennes le long de la facade océanique du Labrador s'est effectué vers 11,000 BP, alors que les glaces avaient déjà disparu du sud-est du Canada. Le rétablissement de conditions interglaciaires fut apparemment diachronique dans les bassins adjacents de l'est du Canada.

Géographie physique et Quaternaire, 1989, vol. 43, n° 3, p. 263-290, 10 fig., 1 tabl.

ISOTOPIC AND PALYNOLOGICAL RECORDS OF THE LATE PLEISTOCENE IN EASTERN CANADA AND ADJACENT OCEAN BASINS

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ABSTRACT Correlations of isotopic and palynological records from deep sea cores in Baffin Bay and Labrador Sea with terrestrial palynological sequences, supported by a few Th/U chronological controls, allow the establishment of a regional climatostratigraphic scheme for the Late Pleistocene climatic fluctuations in eastern Canada. During the climatic optimum of isotopic substage 5e, warmer conditions than present prevailed both on land and in oceanic surface water masses. The 5e/5d transition is marked by an abrupt shift in $\delta^{18}O$ values in Baffin Bay and Labrador Sea as a consequence of ice growth over circumpolar areas of northeastern Canada. From substage 5d to substage 5a, the Baffin Bay border lands experienced glacial conditions while subarctic to cool-temperate and humid climates persisted over Labrador Sea and Atlantic Canada. A short ($<10^4$ yrs) stage 4 is recorded in deep sea cores with high $\delta^{18}O$ values. It corresponds to the Early Wisconsinan southward extension of the Laurentide Ice Sheet dated at *ca.* 80,000 yrs in the central St. Lawrence Lowland. There is no clear evidence of full glacial conditions in the Atlantic Provinces during this episode. Stage 3 (Middle Wisconsinan) corresponds in the isotopic records to large oscillations in $\delta^{18}O$ values suggesting meltwater transits in both Baffin Bay and Labrador Sea. The ice cover remained relatively extensive over eastern Canada, although some areas experienced ice-marginal conditions: in the Atlantic Provinces, notably on Cape Breton Island, hemiarctic to subarctic climate is inferred from palynological records; in the Appalachian foothills of Québec glacial Lake Gayhurst developed some 46,000 yrs ago. During isotopic stage 2 (Late Wisconsinan), the Laurentide Ice Sheet reached its maximum extent while satellitic ice-caps developed over the Atlantic Provinces. In deep sea cores, high $\delta^{18}O$ values mark the full glacial conditions of isotopic stage 2, although slightly lower values in western Labrador Sea indicate discrete but continuous meltwater influxes. An early melting phase of the northeastern margin of the Laurentide Ice Sheet is recorded shortly after 16,700 BP. The full ice-retreat is observed after *ca.* 11,000 BP. At that time, southeastern Canada was already largely ice-free. Finally, the optimum climatic conditions of isotopic stage 1 settled diachronously in the adjacent basins of eastern Canada.

RÉSUMÉ *Stratigraphie isotopique et palynostratigraphie du Pléistocène supérieur dans l'est du Canada et les bassins océaniques adjacents.* La comparaison des enregistrements isotopiques et palynologiques des mers de Baffin et du Labrador avec ceux que fournissent la palynologie et la chronologie U/Th de séquences continentales, autorise l'établissement d'un schéma climatostratigraphique régional représentatif des fluctuations climatiques du Pléistocène supérieur dans l'est du Canada. Pendant l'optimum climatique du stade isotopique 5e, des conditions plus chaudes que celles de l'Actuel ont caractérisé les milieux océanique et continental. La transition 5e/5d est marquée par une augmentation brutale des teneurs en ^{18}O des foraminifères dans les mers de Baffin et du Labrador, en réponse à la formation de calottes glaciaires dans les milieux circumpolaires du nord-est du Canada. Pendant les stades 5d à 5a, le secteur arctique connut des conditions glaciaires, alors que dans la mer du Labrador et les provinces atlantiques des conditions subarctiques à tempérées fraîches persistèrent. Un bref ($< 10^4$ ans) stade 4 se distingue par une augmentation notable des teneurs en ^{18}O dans les séquences océaniques: il correspondrait au développement méridional de l'Inlandsis laurentidien pendant le Wisconsinien inférieur, par ailleurs daté d'environ 80,000 ans dans les basses terres du Saint-Laurent. Rien ne permet cependant de démontrer que des conditions pleinement glaciaires existaient aussi dans les provinces atlantiques. Le stade 3 (Wisconsinien moyen) est caractérisé par des fluctuations des teneurs en ^{18}O des foraminifères indiquant des transits épisodiques d'eau de fonte dans les mers du Labrador et de Baffin. En dépit d'un important volume de glace s'étendant sur l'est du Canada, certaines régions connurent des conditions de marge glaciaire: dans les provinces atlantiques, en particulier à l'île du Cap-Breton, la palynostratigraphie révèle l'existence d'un climat subarctique à hémiarctique; au pied des Appalaches au Québec, le lac proglaciaire Gayhurst s'est formé vers 46,000 ans avant l'Actuel. Au cours du stade 2 (Wisconsinien supérieur), l'inlandsis laurentidien a atteint son volume maximal alors que des calottes satellites se sont formées dans les provinces atlantiques. Dans les carottes océaniques, des fortes teneurs en ^{18}O témoignent des conditions pléniglaciaires du stade 2, bien que des valeurs relativement faibles dans le secteur ouest de la mer du Labrador indiquent des apports d'eau de fonte discrets mais quasi continus. Une phase précoce de fonte glaciaire de la marge nord-est de l'inlandsis se traduit par une baisse des teneurs en ^{18}O peu après 16,700 BP. Le retrait final des glaces laurentidiennes le long de la facade océanique du Labrador s'est effectué vers 11,000 BP, alors que les glaces avaient déjà disparu du sud-est du Canada. Le rétablissement de conditions interglaciaires fut apparemment diachronique dans les bassins adjacents de l'est du Canada.

Manuscrit reçu le 3 novembre 1988; manuscrit revisé accepté le 30 mars 1989.

INTRODUCTION

Pleistocene climatic oscillations, notably those of the last climatic cycle, led to the development and decay of huge ice masses over eastern and northern Canada: the Laurentide Ice Sheet and satellitic ice caps (*cf.* Prest, 1977; Grant, 1977), which overrode most of eastern Canada at least during the Late Wisconsinan, and, northward, the Inuitian Ice Sheet (*cf.* Andrews *et al.*, 1974 et *p.*) whose fluctuations were partly out of phase with those of the Laurentide ice masses. Ice sheet growth and decay were related to oceanic and atmospheric paleocirculation patterns that allowed or restricted penetration of humid air masses at high latitudes (*cf.* Andrews *et al.*, 1972, 1985; Boulton, 1979; Ruddiman and McIntyre, 1979, 1981; Ruddiman *et al.*, 1980; Aksu *et al.*, 1988). In this respect, the adjacent basins of Canada, the Labrador Sea and Baffin Bay, played a major role. They constituted the "primary" transitional basins between ice sheets and open oceans into which large amounts of meltwater had to flow (*cf.* de Vernal and Hillaire-Marcel, 1987b-c). From this viewpoint, the study of Late Quaternary deep sea cores provides an insight into the land/sea/atmosphere interactions over northeastern Canada. Moreover, while most Late Pleistocene continental sequences show important gaps which preclude straightforward correlations and the establishment of regional schemes, the marine records are continuous. Sedimentation rates (*cf.* de Vernal *et al.*, 1987; Causse and Hillaire-Marcel, 1989) were high enough in Baffin Bay and the Labrador Sea to allow high resolution studies of surficial sediments and to give access to direct land-sea climatostratigraphic correlations. Deep sea cores from these basins may therefore provide the best records of the Late Pleistocene climatic changes in the east and north of Canada.

In this paper, we intend to summarize data from recent studies on marine or terrestrial sequences spanning over the Late Pleistocene. The ODP-Leg 105 (Srivastava, Arthur *et al.*, 1987) and site surveys by the CSS-Hudson allowed piston coring of surficial sediments at several sites in Baffin Bay and the Labrador Sea (Fig. 1). Most cores have now been studied and most data will appear in ODP-Leg 105 final report. On land, several sections, notably from the Atlantic Provinces of Canada (de Vernal *et al.*, 1983, 1986; de Vernal and Mott, 1986; Mott and Grant, 1986) provide relatively detailed although incomplete correlative records. Unfortunately, some of the best known Pleistocene sequences from the central St. Lawrence Lowland in Québec (*cf.* Gadd, 1971) cannot be included in this overview since a significant revision of the stratigraphy currently ongoing (*cf.* Lamothe, 1985; Lamothe, 1988; Occhietti, 1988). Recent advances in "absolute" dating of some classical interstadial units from this area (Hillaire-Marcel and Causse, 1989a-b) will however be used as "chronological benchmarks".

For the obvious reason of space limitations, all the data available for each reference site cannot be reported herein and the most relevant results are summarized. The oxygen isotope records on planktonic foraminifers (*Neogloboquadrina pachyderma*, left coiling) are used, allowing direct correlation with the global oceanic ^{18}O-stratigraphy (*e.g.* Shackleton and Opdyke, 1973) and also giving some insights into the ice meltwater transit phases (Hillaire-Marcel *et al.*, 1989; de Vernal and Hillaire-Marcel, 1987b). Summarized palynological data are used to provide correlative paleoceanographic information (*e.g.* dinocyst assemblages; *cf.* de Vernal, 1986 *et p.*) and also, when possible, to establish direct links between the continental and offshore records (pollen and spores; *ibid.*). Finally, the chronological controls, which are indispensable in such a climatostratigraphic review, are yielded by ^{18}O-stage boundaries, a few ^{14}C measurements by AMS technique,

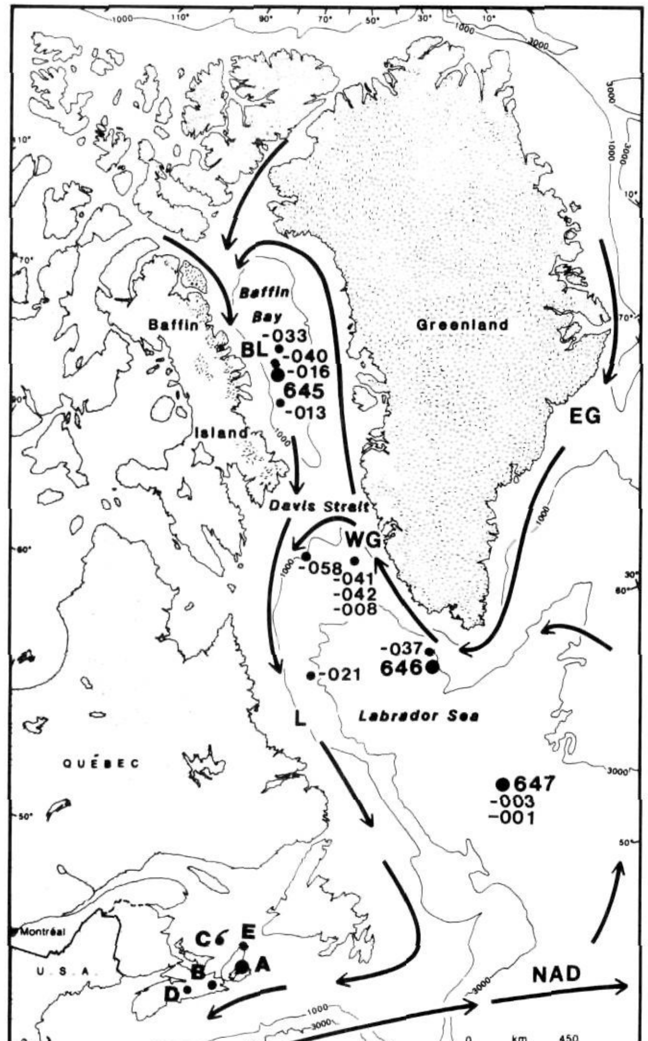


FIGURE 1. Site location map; 645, 646 and 647 refer to the ODP sites; the other numbers indicate the core (LCF, Piston or TWC) locations; A, B, C, D, and E point to the locations of the East Bay-Castle, Addington Forks, East Milford, Le Bassin and Bay St. Lawrence sections respectively. The modern surface water circulation is indicated by arrows.

Carte de localisation des sites de forage: les sites de forage l'ODP sont numérotés 645-646 et 647; les autres numéros correspondent aux sites de carottage par piston (P) et par gravité (TWC); les lettres A, B, C, D, et E indiquent la localisation respective des coupes stratigraphiques de East Bay-Castle Bay, Addington Forks, East Milford, Le Bassin et de la baie Saint-Laurent. La circulation actuelle des masses d'eau superficielle est indiquée par des flèches.

notably on foraminifers, and Th/U measurements on marine (Causse and Hillaire-Marcel, 1989) and terrestrial sequences (Causse and Hillaire-Marcel, 1986; Hillaire-Marcel and Causse, 1989a-b).

BRIEF DESCRIPTION OF THE REFERENCE SITES USED IN THE STUDY

DEEP-SEA SITES

In Baffin Bay, before and during Leg 105 (fall 1985), several piston cores were collected by the CSS-Hudson, notably during cruises 76-029, 77-027 and 85-027. Although the Quaternary stratigraphy of the bay has been intensively studied during the last decade (Aksu and Piper, 1979 *et p.*; Aksu, 1981 *et p.*; Mudie and Aksu, 1984; Andrews *et al.*, 1985; Mudie and Short, 1985; de Vernal, 1986) the chronostratigraphical framework remained uncertain until recently when AMS-^{14}C dates on foraminifers (de Vernal *et al.*, 1987; Hillaire-Marcel *et al.*, 1989; Scott *et al.*, 1989) and paleomagnetic data (Srivastava, Arthur *et al.*, 1987; Thouveny, 1988) clearly demonstrated a short chronology for piston cored sequences (<100,000 years) and generally high but fluctuating sedimentation rates (*ca.* 8 to 20 cm/ka; Hillaire-Marcel *et al.*, 1989). Herein, we refer to cores 85-027-016 (piston-PC & trigger weight-TWC cores; 70°30′N, 64°31′W; water depth 2091 m) and 76-029-033 (P; 71°20′N, 64°16′W; water depth: 2207 m) in which a coherent chronostratigraphy has been defined. In addition, we refer to a *ca.* 22-m composite sequence obtained from the correlation of 5 holes drilled during ODP Leg 105 at Site 645 (Srivastava, Arthur *et al.*, 1987; Fig. 1; 70°27′N, 64°39′W; water depth: *ca.* 2011 m), which constitutes at present the only recovered Baffin Bay sequence spanning the last climatic cycle (*cf.* Hillaire-Marcel *et al.*, 1989). In central Baffin Bay, the upper 10-20 cm of the abyssal surface sediments consist predominantly of hemipelagic deposits mixed with varying proportions of ice-rafted debris (Aksu and Piper, 1979). The subsurface deposits largely include ice-rafted sediments, debrites and turbidites, indicating a strong influence by glacial erosion from adjacent ice sheets, glacio-marine transportation and outwash deposition (Aksu and Piper, 1987).

Several piston cores from the Labrador Sea have already been studied for a climatostratigraphic purpose. Cores from the continental rise and slope off western Greenland (Fillon and Duplessy, 1980; de Vernal, 1986; de Vernal and Hillaire-Marcel, 1987b-c; Aksu *et al.*, 1988; Scott *et al.*, 1989) revealed a stratigraphy spanning 80,000 to 100,000 years, indicating relatively high sedimentation rates of *ca.* 10 cm/ka. The palynological and isotopic records of one of these cores, HU-75-37 (Fig. 1; 59°09′00N-48°23′07W; water depth = 3208 m), *are reported. The drilling of the nearby ODP Site 646 (Fig. 1;* 58°12′56N-48°22′15W; water depth = 3451 m) allowed the recovery of a composite sequence spanning the entire Late Pleistocene episode, to which we also refer (Aksu *et al.*, 1989). Quaternary sediments of core HU-75-37 and Site 646 consist of hemipelagic mud with variable proportions of ice-rafted sand. In the south central Labrador Sea, the sedimentary sequences drilled during Leg 105 at the Site 647 and cored during the Site survey cruise (84-030-001, −002 and −003; 53°19′79N-45°15′85W; water depth = ~3771 m) revealed relatively low sedimentation rates of *ca.* 4.5 cm/ka (de Vernal and Hillaire-Marcel, 1987c; Srivastava, Arthur *et al.*, 1987; Causse and Hillaire-Marcel, 1989; Scott *et al.*, 1989). We refer to cores 84-030-001 and −003 spanning the last climatic cycles and which have been sampled at narrow intervals (~ 5 cm) in order to provide an accurate time resolution. At that Site sediments consist of foraminifera oozes alternating with grayish and brownish hemipelagic mud.

South of Davis Strait, many cores have been studied by Filion and Duplessy (1980), Aksu and Mudie (1985) and Fillon and Aksu (1985). *More recently, cores were collected during* cruise 87-033 of the CSS-Hudson. Herein, the stratigraphy of cores 87-033-008 (TWC & LCF; 62°38′91 N, 53°53′07 W; water depth: 2424 m) is discussed in addition to the one of piston cores collected during cruise HU-75 (*cf.* Fillon and Duplessy, 1980): HU-75-41 (62°39′ N, 53°53′ W; water depth: 2381 m); HU-75-42 (62°39′ N, 53°54′ W; water depth: 2403 m). In these cores from southeast Davis Strait, the sediments mainly consist of hemipelagic mud with abondant ice rafted debris, and most sequences do not exceed a few tens of thousand years. In cores from southwest Davis Strait, the presence of gravity flow and turbidites have been noted by Aksu and Mudie (1985).

Finally, in the Western Labrador Sea area, off Labrador coast, one core (84-030-021 TWC & PC; 58°22′06 N, 57°30′42 W; water depth: 2853 m) allowed some insight into the last ice maximum and subsequent retreat history (*cf.* de Vernal and Hillaire-Marcel, 1987b). The study of this core adds new data to initial studies of east Canadian glacial history which were carried out on cores from the Labrador shelf (Vilks and Mudie, 1978, 1983; Mudie, 1980; Mudie *et al.* 1984; Scott *et al.*, 1984; Josenhans *et al.*, 1986). As may be expected at the margin of the Laurentide Ice Sheet, Late Pleistocene sediments of core 84-030-021 consist of sandy to gravelly clayey mud. The sequence is topped by *ca.* 2 m of hemipelagic silty mud.

TERRESTRIAL SITES

The best preserved records of the Late Pleistocene are found in places which experienced ice marginal conditions during a large part of the Last Ice Age. Such was the case of the Great Lakes, where some sections provided relatively unique sedimentary sequences (*cf.* Dreimanis and Karrow, 1972; Dreimanis, 1977; Karrow, 1984) and also of the Atlantic Provinces (Grant, 1977; Prest, 1977; Grant and King, 1984; de Vernal *et al.*, 1986). Since the latter allow direct correlations with the marine records, we will essentially refer to them.

On Cape Breton Island, recent work by de Vernal and Mott *(1986) settled the base of a palynostratigraphy for the Late* Pleistocene that can be used for reference. A composite sequence from East Bay and Castle Bay provided a record spanning apparently over the last Interglacial and a fair part of the Wisconsinan glaciation. At East Bay (45°59′N; 60°27′W), infilling of a karst depression in Mississipian gypsum by gravels and silty lenses preserved remains of organic rich deposits that were assigned from Th/U measurements on wood remains (de Vernal *et al.*, 1986; Causse and Hillaire-Marcel, 1986) to episodes correlative of the isotopic substages 5e, 5a and stage 3. At Castle Bay (45°55'N; 60°39'W), the Middle Wisconsinan episode is expanded in a *ca.* 15 m sequence of finely laminated silts containing disseminated organic matter with a *ca.* 1.5 m organic-rich silt zone at the base, that overlie an indurated reddish gravel. The lateral occurrence of interbedded deltaic sands probably deposited by a meltwater stream and the sporadic presence of marine diatoms (Lortie *et al.*, 1984), which can only be explained by glacio-isostatic depression of the area during the sedimentary episode, suggest the proximity of an ice margin. At both sites, directly above the sequences or laterally, the Late Wisconsinan till is observed.

Partly correlative sequences will be referred to. In mainland Nova Scotia, organic-rich sedimentary units at East Milford (Prest, 1970; Mott *et al.*, 1982) and Addington Forks (MacNeil, 1969; Mott *et al.*, 1982) were also assigned to substages of the last Interglacial (*cf.* also de Vernal and Hillaire-Marcel, 1987a). On the Îles de la Madeleine, at Le Bassin (Mott and Grant, 1986), a *ca.* 1.4 m sequence beginning with sandy-silts, followed by a thin layer of peat overlain by clays topped by gravel, yielded a relatively continuous record of the climatic optimum of the last Interglacial (*cf.* de Vernal and Hillaire-Marcel, 1987a). This sequence is unique since deposition apparently began at the stage 6/5 transition (*ibid.*).

As mentioned earlier in this paper, we will not refer to some of the best known Pleistocene sections of southern Québec, since significant stratigraphical revisions have been undertaken by Lamothe (1988) and Occhietti (1988). We will however mention two lithostratigraphic units: the Lake Deschaillons varves from the central St. Lawrence Lowland (Karrow, 1957, 1984; Gadd, 1971) and the Lake Gayhurst varves (McDonald, 1969; McDonald and Shilts, 1971) from the Appalachian foothills of Québec. In both cases, early diagenetic precipitation of carbonate concretions allowed the establishment of well controlled Th/U ages of 79,800 ± 1,400 and 46,000 ± 1,000 yrs respectively (*cf.* Hillaire-Marcel and Causse, 1989b; Hillaire-Marcel *et al.*, 1988). These time-marks constraint respectively the earliest Wisconsinan Laurentide ice advance southward and a later significant retreat during Middle Wisconsinan time.

^{18}O RECORDS

It should be mentioned first that all isotopic records on planktonic foraminifers (*i.e. Neogloboquadrina pachyderma* left coiling) from Baffin Bay and the Labrador Sea show larger $\delta^{18}O$ glacial/interglacial ranges than those from "open" oceans [*ca.* 1.8‰ in the Caribbean Sea (Emiliani, 1966) or *ca.* 1.4‰ in the Pacific Ocean (Shackleton and Opdyke, 1973)]: ranges of 2 to 3‰ are actually observed in the Labrador Sea and Baffin Bay records (Fig. 2). Two factors account for this difference:

(1) A sampling artefact: much higher sedimentation rates in the adjacent basins of Canada result in a much higher time resolution. For example, in cores 84-030-001/003 (southern central Labrador Sea), 1 (003) or 2 (001) cm-thick samples were collected at 5 or 10 cm intervals. Neglecting bioturbation effects, each sample "integrates" a time interval of *ca.* 200 or 400 yrs respectively (*cf.* de Vernal and Hillaire-Marcel, 1987c). Comparatively, a 2 cm-thick sample in a Carribean core represents *ca.* 1000 yrs of sedimentation: a time interval of the same order of magnitude than that required for homogenization of oceanic water masses (10^3 yrs: Shackleton, 1977; 3×10^3 yrs: Mix and Ruddiman, 1984). A lesser inertia then characterizes ^{18}O-records in the Labrador Sea. For the purpose of comparison between the two records, the ^{18}O profiles of Figure 2E should be "smoothed" with a "running mean" of *ca.* 5 successive samples. The glacial/interglacial $\delta^{18}O$ ranges would then be reduced from *ca.* 3‰ to *ca.* 2.4‰ (a value still larger than that observed in "open" oceans; *cf.* item 2 below). This sampling artefact is well demonstrated when comparing the ^{18}O-profiles of the two nearby cores 001/003: although very similar to that of core 001, the ^{18}O-record of core 003 shows a slightly larger range of values and tiny oscillations that are "hidden" in the profile of core 001. Actually, 15 cm^3 samples were used in core 001 (Scott *et al.*, 1989); 10 cm^3 samples in core 003 (de Vernal and Hillaire-Marcel, 1987c). This minor sampling discrepancy is already responsible for actual but misleading differences in $\delta^{18}O$ values.

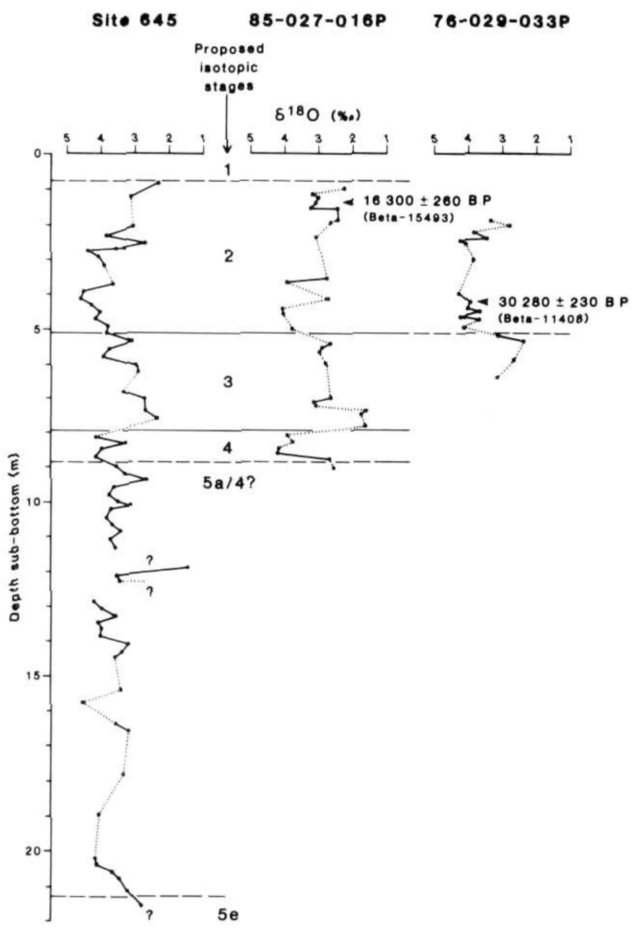


FIGURE 2A. The ^{18}O-records in Baffin Bay (cf. Hillaire-Marcel *et al.*, 1989).

Les variations des teneurs en ^{18}O dans la mer de Baffin (cf. *Hillaire-Marcel* et al., *1989*).

(2) The specificity of the Labrador Sea and Baffin Bay basins is the second factor accounting for the large amplitude shifts observed in $^{18}O/^{16}O$ ratios. Actually, maximum values during glacial stages are relatively similar to those measured in most deep sea records when allowing for a temperature-driven isotopic fractionation in high latitude planktonic foraminifers. Departure from average ^{18}O-records is essentially due to the very light peaks of interglacial or interstadial episodes. In both basins, huge quantities of meltwater from the Laurentide Ice Sheet and its satellitic ice caps transited during such episodes before complete homogenization in the world oceans. Beyond temperature effects, the very low $\delta^{18}O$ values observed in planktonic foraminifers from these "transitional" basins would also respond to a relative dilution of their surface water masses by meltwaters.

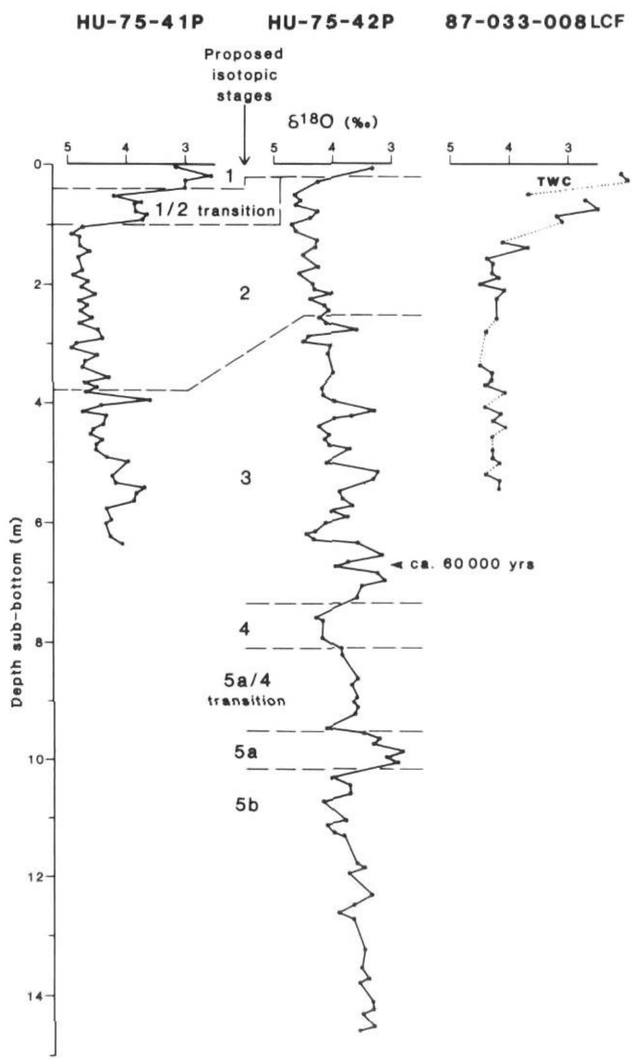


FIGURE 2B. The ^{18}O-records in Davis Strait area (data from cores HU-75-41 and HU-75-42 are from Fillon and Duplessy, 1980; the core 87-033-008 results are not yet published).

Les variations des teneurs en ^{18}O dans le détroit de Davis (les données des carottes HU-75-41 and HU-75-42 sont de Fillon et Duplessy, 1980; les résultats de la carotte 87-033-008 n'ont pas encore été publiés).

PRE-LATE PLEISTOCENE DATA

Stage 6/5 transition, corresponding to the Illinoian/Sangamonian ice-retreat in the North American stratigraphy and to the formal Middle/Late Pleistocene subdivision commonly accepted, is well documented at ODP Site 646 and in site survey cores from Site 647 (cores 84-030-001 and -003) in the Labrador Sea (Fig. 2: C and E). In both areas slightly higher $\delta^{18}O$ values are recorded during stage 6 (as high as +4.7/+4.9‰) than during isotopic stage 2 (*ca.* +4.5‰). With respect to stratigraphy of eastern Canada, it seems likely that the Illinoian ice maximum was more severe than the Wisconsinan one: some of the ice-marginal features observed on shelves off Labrador (Josenhans *et al.*, 1986) and Nova Scotia (King and MacLean, 1976) very probably correspond to this maximum ice extension. Two of the ^{18}O records (Site 646: Fig. 2C; core 84-030-003: Fig. 2E) show a two-step transition, not unlike terminations 1A/1B (Duplessy *et al.*, 1981) at the Pleistocene-Holocene transition.

THE BAFFIN BAY RECORDS

The actual ^{18}O-records in Baffin Bay (Hillaire-Marcel *et al.*, 1989; Fig. 2A) show very large amplitude shifts (from +0.3 to +4.6‰), although most values range from +2.5 to +4.6‰ (Fig. 2A) with the exception of samples containing very few foraminifers. Today, the upper layer, from 0 to 250 m

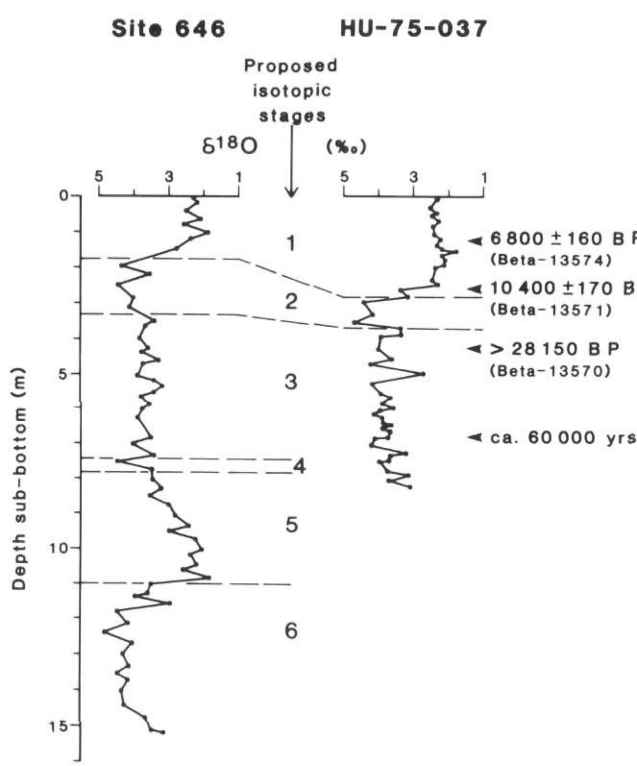


FIGURE 2C. The ^{18}O-records off southwest Greenland (the composite record of site 646 is from Aksu *et al.*, 1989; the core HU-75-37 data are first published in this paper).

Les variations des teneurs en ^{18}O au sud-ouest du Groenland (les données de la séquence composite du site 646 sont empruntées aux travaux d'Aksu et al.*, 1989; les données de la carotte HU-75-37 sont inédites).*

deep, has temperatures ranging from -1 to $+1.8$°C (Muench, 1971). It seems unreasonable to hypothesize higher temperature at this latitude during isotopic stages 4, 3 and 2. Hence, most of the ^{18}O changes in planktonic foraminifers reflect changes in the isotopic composition of the surface water. Assuming an isotopic composition range of *ca.* $-30/-20$‰ *vs* SMOW for meltwater from the surrounding ice caps during the Wisconsinan (Dansgaard *et al.,* 1971; Broecker, 1975), surface water paleosalinities from approximately 31 to 35‰ can be extrapolated from modern conditions in the Bay (Tan and Strain, 1980; Bédard *et al.*, 1981). Rapid mixing and/or evacuation of the ice meltwater was probable, in view of the brevity of the "^{18}O-depleted" episodes.

In Figure 2A, the short meltwater peaks of the ^{18}O-record were screened out (dashed lines) by retaining only samples containing a minimum of 4 specimens·cm^{-3}. Results on samples with lower concentrations may be partly misleading: possible reworked fossils (bottom currents, ice-rafting, bioturbations) weight too much in the numbers obtained; the numbers cannot be checked on duplicate samples (*cf.* Hillaire-Marcel *et al.*, 1989). The filtered profiles of Figure 2A are then comparable to those we will see in the Labrador Sea. On the basis of the highest $\delta^{18}O$ values ($> +4$‰) assigned to the isotopic stages 2 and 4, a good correlation is observed between the three studied cores and a relatively clear isotope stratigraphy can be derived.

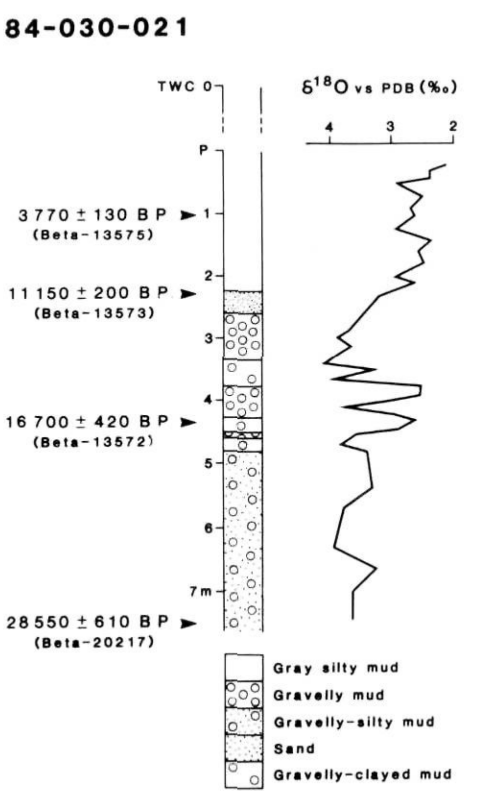


FIGURE 2D. The ^{18}O-records off central Labrador (*cf.* de Vernal and Hillaire-Marcel, 1987b).

Les variations des teneurs en ^{18}O au large du Labrador (cf. *de Vernal et Hillaire-Marcel, 1987b*).

All cores collected in central Baffin Bay show a short Holocene record (~ isotopic stage 1): $\delta^{18}O$ values lower than $+3$‰ appear only at or above 50 cm sub-bottom. In core TWC-85-027-016, an AMS ^{14}C date of 10,590 ± 130 BP at *ca*. 50 cm sub-bottom (Scott *et al.*, 1989) confirms the position of stage 2/1 transition. A similar age (*ca.* 10,500 BP) has been previously reported at a depth of *ca*. 50 cm in core 77-027-017 collected north of Davis Strait (Aksu, 1981).

Isotopic stage 2 is represented by relatively thick deposits in all Baffin Bay cores, which show $\delta^{18}O$ values above $+4$‰ between *ca*. 3 and 4 m sub-bottom; these values reflect full

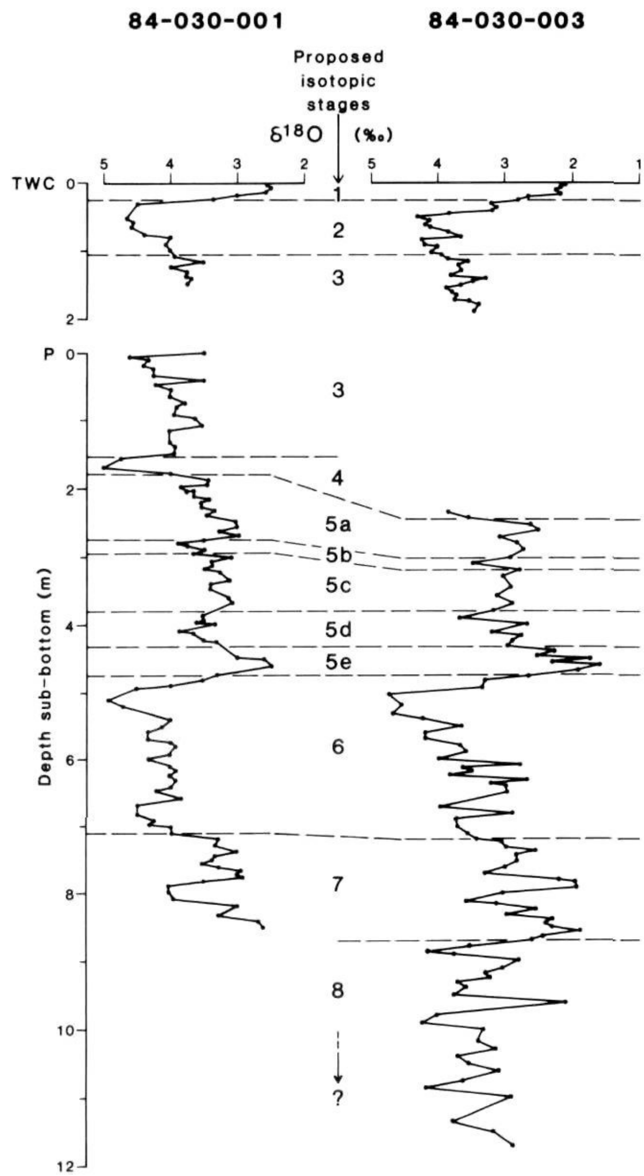


FIGURE 2E. The ^{18}O-records in south central Labrador Sea (core 84-030-001 record is from Scott *et al.*, 1989; core 84-030-003 record was published by de Vernal and Hillaire-Marcel, 1987b,c.).

Les variations des teneurs en ^{18}O dans le secteur méridional du centre de la mer du Labrador (les données de la carotte 84-030-001 sont empruntées à Scott et al., *1989; celles de la carotte 84-030-003 ont été publiées par de Vernal et Hillaire-Marcel, 1987b,c.*

glacial conditions and near-standard marine water at the surface. These conditions apparently settled slightly before *ca.* 30,000 BP, as indicated by an AMS ^{14}C age on core 76-029-033. Stage 3/2 transition is well marked in all profiles, with a sharp shift from lower values ($\delta^{18}O < +3‰$) at *ca.* 4-5 m sub-bottom. From these data, very high sedimentation rates may be interpolated during stage 2 (*ca.* 0.15-0.20 mm.yr^{-1}).

Stage 3 is well bounded by sharp ^{18}O-shifts in cores 645G-1H and 85-027-016. It shows a succession of light peaks in the complete record (*cf.* Hillaire-Marcel *et al.*, 1989); the deepest one, in the lower part of stage 3, is also well recorded in the "filtered" profile of Figure 2A with δ values of *ca.* 1.5‰. The latter corresponds to the lightest peak and is observed in all ^{18}O high-resolution records of Baffin Bay (see Aksu, 1981, 1985: cores 77-027-017 and 76-029-040). It definitely reflects a significant ice-retreat (at least over Arctic Canada) during the Middle Wisconsinan, as also shown by on-land stratigraphies (e.g. Andrews *et al.*, 1984).

A very short stage 4 is present in all cores, with $\delta^{18}O$ values again exceeding +4‰ at a depth of *ca.* 8 m sub-bottom.

The lower part of the isotopic stratigraphy, in ODP-cores 645, down to *ca.* 22 m sub-bottom, is not as clear as the upper part of the sequence. Relatively large amplitude shifts in ^{18}O and in reworked palynomorphs (see below) indicate episodes of glacial activity alternating with phases of meltwater discharge. Indeed, $\delta^{18}O$ values exceeding +4‰ point to ice-growth over surrounding lands, as already proposed on theoretical grounds by Boulton (1979) and from field data on Baffin Island by Andrews and others (1984). Because of the low number of data points, the poor core recovery and probable hiatuses in the composite record of Figure 2A, any substage stratigraphy in isotopic stage 5 would be speculative. From micropaleontological data, as we will see further on, the lowermost part of the composite sequence probably belongs to substage 5e. As a whole, stage 5 would then be characterized by sedimentation rates on the same order of magnitude as those of stage 3 (*ca.* 0.20 mm.yr^{-1}).

THE DAVIS STRAIT RECORDS

The three ^{18}O-profiles from the Davis Strait (Fig. 2B) show a high degree of similarity, particularly those of cores HU-75-42 (Fillon and Duplessy, 1980) and 87-033-008 (new set of data). A much smaller range of $\delta^{18}O$ variations ($\leq 2‰$) is observed in the Davis Strait cores by comparison to the Baffin Bay record. Beyond a clear stage 2/1 transition (above 100 cm sub-bottom), a relatively continuous depletion in ^{18}O is recorded from the maximum value of stage 2 ($\geq +4.5‰$) down to the minimum value of *ca.* +3‰ below 10 m sub-bottom in core HU-75-42 that is assigned to the isotopic stage 5 (5a?; *cf.* Fillon and Duplessy, *ibid.*). We must therefore look at the proposed isotopic transitions with some circumspection. Here again, light values are observed notably at the beginning of stage 3: the strong melting event of the stage 4/3 transition-early stage 3 seems as well recorded south of Davis Strait as it was in Baffin Bay.

Isotopic stage 4 is poorly marked and probably very short in all available records and the amplitude of stage 5a-4 transition isotopic shift is not really larger than that of stage 4/3 transition (*cf.* also Aksu and Mudie, 1985).

In core HU-75-42, the relatively high $\delta^{18}O$ values observed at *ca.* 11 m sub-bottom and tentatively assigned to isotopic substage 5b can also be interpreted as an effect of a significant ice extension, at least over Arctic Canada.

Unfortunately, the lower part of the isotopic stage 5 could not be recovered by piston coring due to the high sedimentation rates (ca. 0.1 mm.yr^{-1}). During the CSS-Hudson cruise 87-033, the long coring facility (LCF) that was required for further penetration in the sediments was previously lost while coring in Baffin Bay.

A few piston cores from the Davis Strait area were previously studied by Aksu and Mudie (1985) and Mudie and Aksu (1984), notably cores 77-5-1, 77-1-2 and 77-027-017 for their palynological content and foraminiferal assemblages and isotopic composition. The authors suggest a stratigraphy spanning isotopic stages 9 to 1 for the relatively short (<10 m) sequences. This would imply sedimentation rates *ca.* 5 times lower than those recorded at other nearby sites. It is our belief that they misinterpreted the ^{18}O record, which more likely spans part of the last glacial cycle (stage 1 to stage 4?). Therefore, it is difficult to refer to their interpretation of paleoceanographical changes in the present paper. A detailed discussion on this subject can be found in de Vernal *et al.* (1987).

THE EASTERN LABRADOR SEA RECORDS

Off Greenland, the composite record of ODP-Site 646 (Aksu *et al.*, 1989) and that of core HU-75-37 (Fig. 2C) show a slightly larger range in $\delta^{18}O$ values than that observed just south of Davis Strait: from a minimum of *ca.* +2‰ during isotopic stages 1 and 5e, to a maximum of ca. +4.4‰ during stage 2. It can also be seen from these numbers that the whole record notably in core HU-75-37 is shifted towards lighter values. A similar shift was also observed in core 84-030-006 (Aksu *et al.*, 1988). It seems likely that beyond the temperature gradient, which can partly account for the differences observed between the two areas, the latter also experienced the persistence of slightly more diluted surface waters throughout most of the Last Ice Age, eventually in response to relatively continuous meltwater discharge from the nearby Greenland Ice Sheet margin.

Another peculiarity of the ^{18}O records off Greenland is the relatively low sedimentation rates that can be interpolated for the isotopic stage 2 compared to those of stage 1 (Fig. 2C), which is also shown by a strong excess in ^{230}Th over ^{234}U at ODP Site 646 (Causse and Hillaire-Marcel, 1989). Interpolation between isotopic stage boundaries yield a mean sedimentation rate of *ca.* 0.1 mm.yr^{-1} throughout the whole sequence. We also note here the occurrence of large oscillations during stage 3 in response to meltwater discharge episodes and also the very discrete stage 4 that is barely distinguishable in ^{18}O-curves. Tephrostratigraphical correlations from Fillon and Duplessy (1980) assign an ash rich layer observed at *ca.* 6.7 m sub-bottom in core HU-75-37 to the earliest "light" peak of stage 3. On this basis, isotopic stage 4 seems to be represented here by a couple of "heavy" values at *ca.* 7 m sub-bottom. This core very probably ends in isotopic substage 5a, where unusually high ^{18}O-contents (> + 3.1‰) are observed. This is apparently confirmed by the composite sequence of ODP-Site 646, although isotopic stage 5 subdivisions are not as clear as it could be expected.

THE WESTERN LABRADOR SEA RECORD

Off Labrador coast, one core (84-030-021; Fig. 2D) collected on the continental rise showed a relatively undisturbed sedimentary sequence suitable for isotopic studies. A few AMS ^{14}C measurements (de Vernal and Hillaire-Marcel, 1987b) show that the record spans over the last ice maximum and retreat phases (basal age of *ca.* 28,000 BP). Direct correlations with the shelf stratigraphy (Josenhans, 1983; Josenhans *et al.*, 1986; Fillon and Harmes, 1982; Osterman *et al.*, 1985) were already proposed by de Vernal and Hillaire-Marcel (1987b). Although short in time, this record is of importance because it can be directly associated with the glacial history on the coastal area of Labrador. $\delta^{18}O$ values in *Neogloboquadrina pachyderma* (left coiling) define a relatively narrow range between isotopic stages 2 and 1 with respect to the core location: from a maximum of *ca.* + 4‰ to a minimum of *ca.* + 2‰. Here again, the low values observed during the last ice maximum cannot be attributed to a temperature effect but to continuous meltwater runoff from the Laurentide Ice Sheet margin that maintained a slight dilution of surface waters. Another interest of this profile is its high resolution recording of the deglaciation: shortly after 16,700 ± 420 BP (Beta 13572), a 1 to 1.5‰ shift in $\delta^{18}O$ values is observed; it indicates a strong but brief episode of dilution of surface water masses. The corresponding large meltwater input through the Labrador Current may be due to significant melting either along the northeastern Laurentide ice margin or from the Inuitian ice cap or both. Subsequent recurrence of high $\delta^{18}O$ values (*ca.* + 4‰ again) suggests restabilization of the ice sheet(s) until *ca.* 11,000 BP, when final retreat is shown by a regular shift to "lighter" values.

Similar early warming and melting events were also recorded in cores from Cartwright Saddle (54°N) on the Labrador shelf (Vilks and Mudie, 1978; Mudie *et al.*, 1984). Since most of the ^{14}C ages on these cores were obtained from measurements on total organic carbon, precise correlations with our record are uneasy.

THE SOUTH CENTRAL LABRADOR SEA RECORDS

The ODP-Site 647 has a strategic location between the northern Labrador Sea and the North Atlantic Ocean. The "classical" aspect of the ^{18}O-profiles of Figure 2E should come as no surprise. Both site survey cores (84-030-001 and 003) define a clear ^{18}O stratigraphy at least from ^{18}O stage 7 to stage 1 and allow thus direct correlations with North Atlantic records (de Vernal and Hillaire-Marcel, 1987c; Scott *et al.*, 1989). In core 003, a gap is observed between the TWC- and PC-record; core 001 seems complete.

Below a short stage 1 characterized by relatively "light" values (+ 2.5/+ 2.2‰ respectively in the "sensitive" record 003 and in the smoother record 001), a typical two-step stage 2/1 transition is observed (core 003). Stage 2 (25-100 cm sub-bottom in TWC-001 and 003) is well-bounded and corresponds to relatively low sedimentation rates (*ca.* 0.03 mm.yr^{-1} *vs* the mean rate of 0.05 mm.yr^{-1} that can be interpolated from ^{18}O stage boundaries throughout the whole sequence). Stage 3 again shows large oscillations indicating that direct meltwater influence was still noticeable at this remote site. Stage 4 is well shown in core 001 by a sharp shift towards "heavy" values. Postulating sedimentation rates similar to those of stage 2 during stage 4, the latter seems brief (<5000 yrs). An "expanded" stage 5 is observed in both records. Substages are well marked, notably 5b and 5d, where $\delta^{18}O$ values as high as + 3.9‰ are observed. They point toward significant changes in the basin isotopic composition and temperature during these episodes of ice growth in Arctic areas (see above).

PALYNOLOGICAL RECORDS

BAFFIN BAY

Quaternary sediments from Baffin Bay are generally characterized by their paucity in calcareous and siliceous microfossils (Srivastava, Arthur *et al.*, 1987). The palynological content is also low in most samples (*cf.* Mudie, 1980, 1982; Mudie and Short, 1985; de Vernal, 1986; de Vernal *et al.*, 1987; Hillaire-Marcel *et al.*, 1988; de Vernal and Mudie, 1988; Fig. 3A-B-C). All analysed cores show a similar dinoflagellate cyst stratigraphy summarized in Figures 3D-E-F. The subrecent assemblages of the uppermost 10 to 20 cm in the sedimentary sequence are characterized by relatively high concentrations, up to 2000 cysts·cm^{-3}, and the dominance of *Operculodinium centrocarpum* and *Spiniferites elongatus*. This assemblage may be associated with the modern subarctic conditions in surface water masses, which are favored by the penetration of the subarctic West Greenland current into Baffin Bay (*cf.* also Mudie and Short, 1985). Subarctic conditions revealed by this dinocyst assemblage have prevailed in Baffin Bay only since the Middle or Late Holocene as demonstrated by the chronostratigraphy of core 85-027-016 TWC (Scott *et al.*, 1989) and suggested by correlations between the Baffin Bay and western Labrador Sea palynostratigraphies (de Vernal, 1986). Downcore throughout most of the central Baffin Bay sequences, the dinoflagellate cyst occurrences are rare with exceptions of a few peaks of *Brigantedinium simplex* accompanied by *Multispinula minuta*. The low dinocyst concentrations recorded throughout most of the Late Pleistocene interval suggest a low primary productivity, likely related to the existence of a dense or continuous pack ice cover as in the modern Arctic Ocean (*cf.* Mudie, 1985). The brief episodes of higher productivity are associated with cold conditions and low salinity (<30‰) in surface water masses (Mudie and Short, 1985; de Vernal *et al.*, 1987). At the base of the 22 m composite sequence from ODP Site 645, a relatively rich dinocyst assemblage characterized by *Bitectatodinium tepikiense, Spiniferites elongatus, Operculodinium centrocarpum* and *Brigantedinium simplex* indicates subarctic conditions in ad-

FIGURE 3A. Palynological record of Baffin Bay: palynomorph concentrations in the composite sequence of site 645 (*cf.* Hillaire-Marcel *et al.*, 1989).

La palynostratigraphie de la mer de Baffin: concentration des palynomorphes dans la séquence composite du site 645 (cf. *Hillaire-Marcel* et al., *1989).*

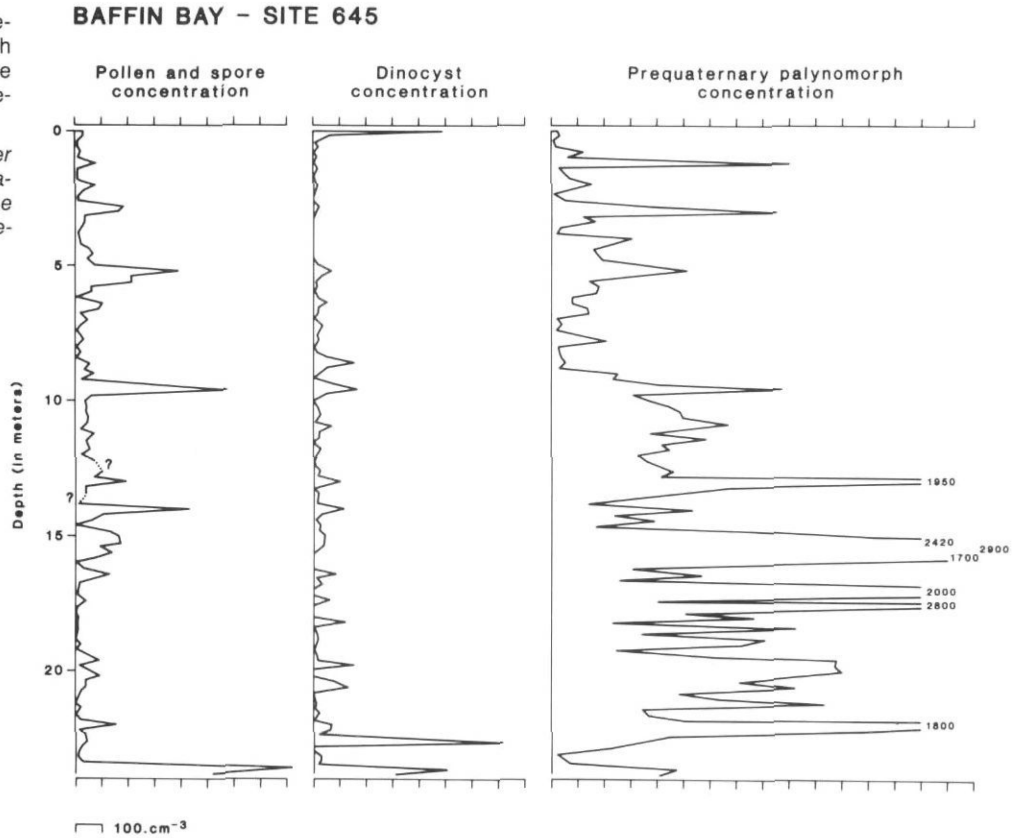
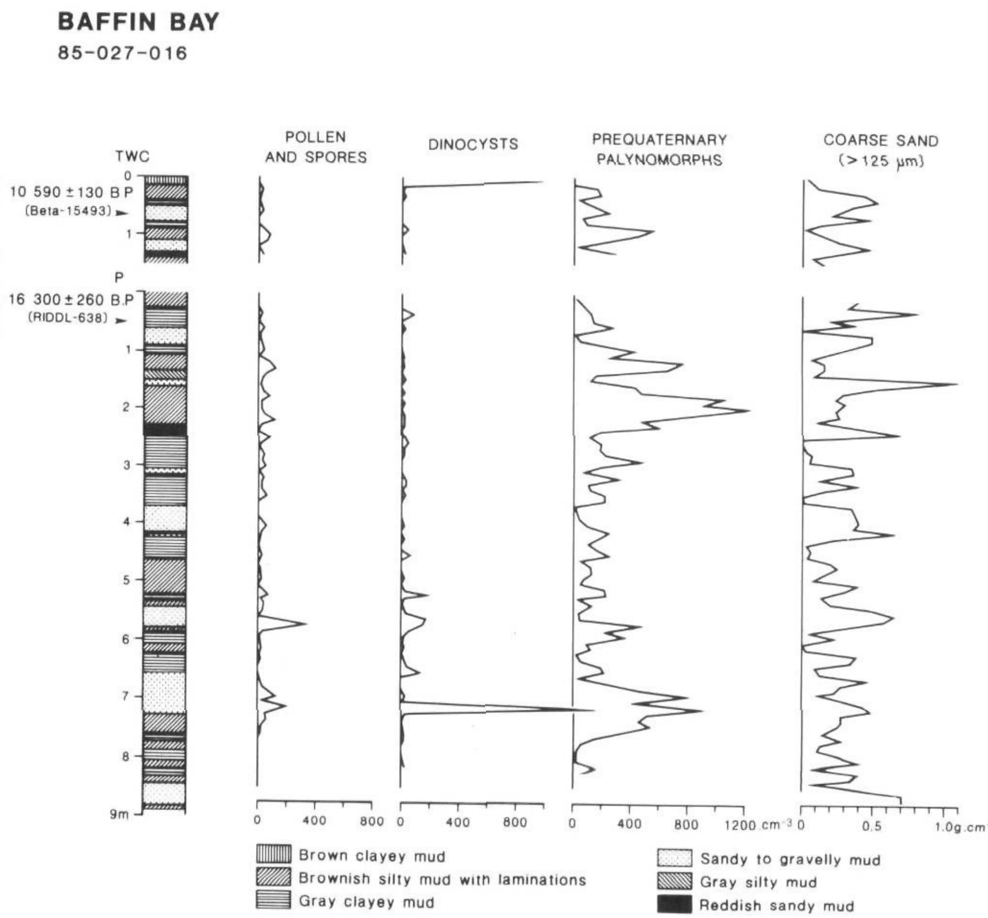


FIGURE 3B. Palynological record of Baffin Bay: lithostratigraphy, palynomorph and coarse sand concentrations in cores 85-027-016 P et TWC (*cf.* Hillaire-Marcel *et al.*, 1989).

La palynostratigraphie de la mer de Baffin: lithostratigraphie, concentration des sables grossiers et des palynomorphes dans les carottes 85-027-016 P et TWC (cf. *Hillaire-Marcel* et al., *1989).*



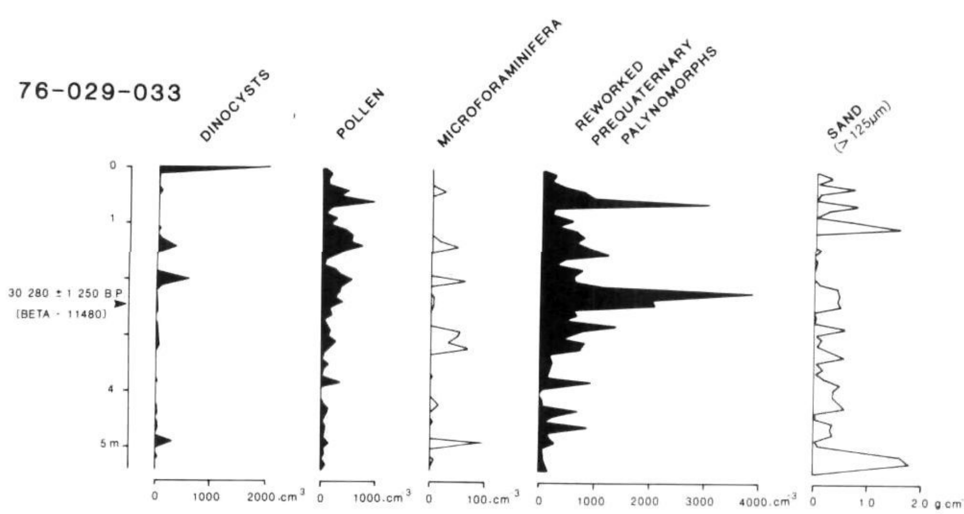


FIGURE 3C. Palynological record of Baffin Bay: palynomorph and coarse sand concentrations in core 79-029-033P (*cf.* de Vernal *et al.*, 1987).

*La palynostratigraphie de la mer de Baffin: concentration des palynomorphes et des sables grossiers dans la carotte 79-029-033P (*cf. *de Vernal* et al.*, 1987).*

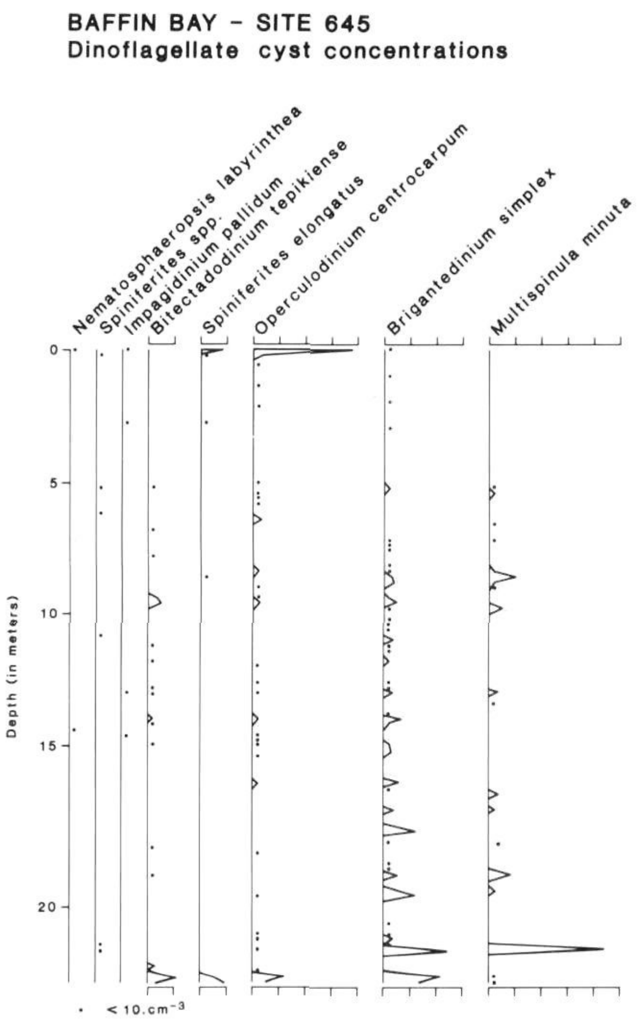


FIGURE 3D. Palynological record of Baffin Bay: dinoflagellate cyst record at Site 645 (*cf.* Hillaire-Marcel *et al.*, 1989).

*La palynostratigraphie de la mer de Baffin: diagramme de concentration des dinokystes au site 645 (*cf. *Hillaire-Marcel* et al.*, 1989).*

dition to relatively low salinity. This assemblage probably corresponds to the climatic optimum of the last Interglacial, *i.e.* to substage 5e.

The Quaternary pollen and spore concentrations are generally very low in Pleistocene sediments from Baffin Bay (< 100·cm^{-3}; Mudie and Short, 1985; de Vernal, 1986; de Vernal *et al.*, 1987; Hillaire-Marcel *et al.*, 1988; Fig. 3A-B-C). Consequently, detailed interpretation is not possible, especially when taking into account the possibility of a reworking with bottom currents or ice-rafting (de Vernal *et al.*, 1987). Nevertheless, the low pollen influxes are indicative of a reduced vegetation cover on surrounding lands. In addition, the dominance of *Pinus* in most samples reveals inputs from a southern origin and also points to the low terrestrial productivity of the regional vegetation. At the base of the composite 22-m sequence from Site 645, however, a relatively rich pollen assemblage is observed. It is characterized by high pollen concentrations, up to 800 grains·cm^{-3}, and significant proportions of *Picea, Betula, Alnus crispa,* herbs and *Sphagnum* (*ca.* 50%) in addition to *Pinus*. This assemblage, which corresponds to the isotopic substage 5e, suggests relatively high regional terrestrial productivity, the existence of a shrub tundra vegetation over Baffin Bay and possibly over Greenland, and probably relates also to a northward shift of the boreal forest limit (Hillaire-Marcel *et al.*, 1989).

In the palynological record from Baffin Bay, one of the main features is the abundance of reworked pre-Quaternary palynomorphs, which is indicative of glacial erosion, transport and outwash deposition from the Arctic Archipelago where the original sedimentary units outcrop. On the basis of this abundance, the most severe glacial activity in eastern Arctic Canada occurred early during the Late Pleistocene, *i.e.* during the isotopic stage 5 (Fig. 3A), as already suggested from the continental stratigraphy (*cf.* for example Andrews *et al.*, 1984; Andrews and Miller, 1984; Klassen, 1985).

SOUTHEAST DAVIS STRAIT

Cores 87-033-008TWC and LCF represent a part of the Late Pleistocene (<100,000 years). The uppermost 30 cm

FIGURE 3E. Palynological record of Baffin Bay: dinoflagellate cyst record in cores 85-027-016 TWC and P (*cf.* Hillaire-Marcel *et al.*, 1989).

La palynostratigraphie de la mer de Baffin: diagramme de concentration des dinokystes des carottes 85-027-016 TWC et P (cf. *Hillaire-Marcel* et al., *1989*).

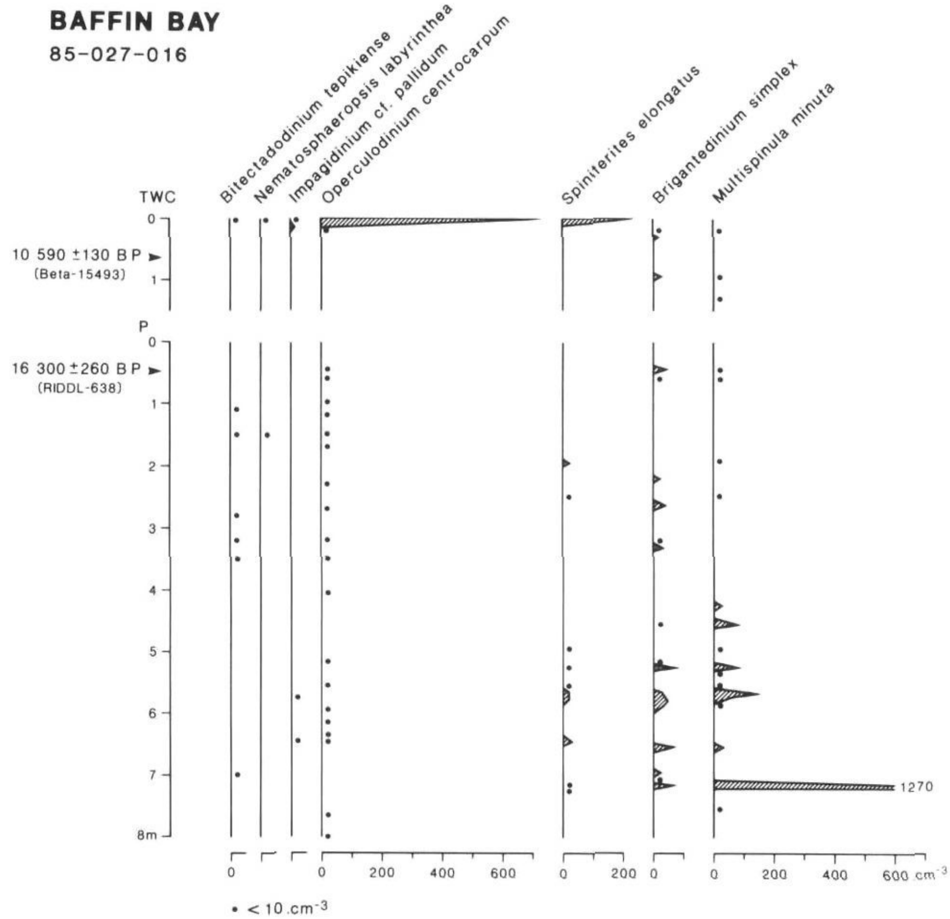
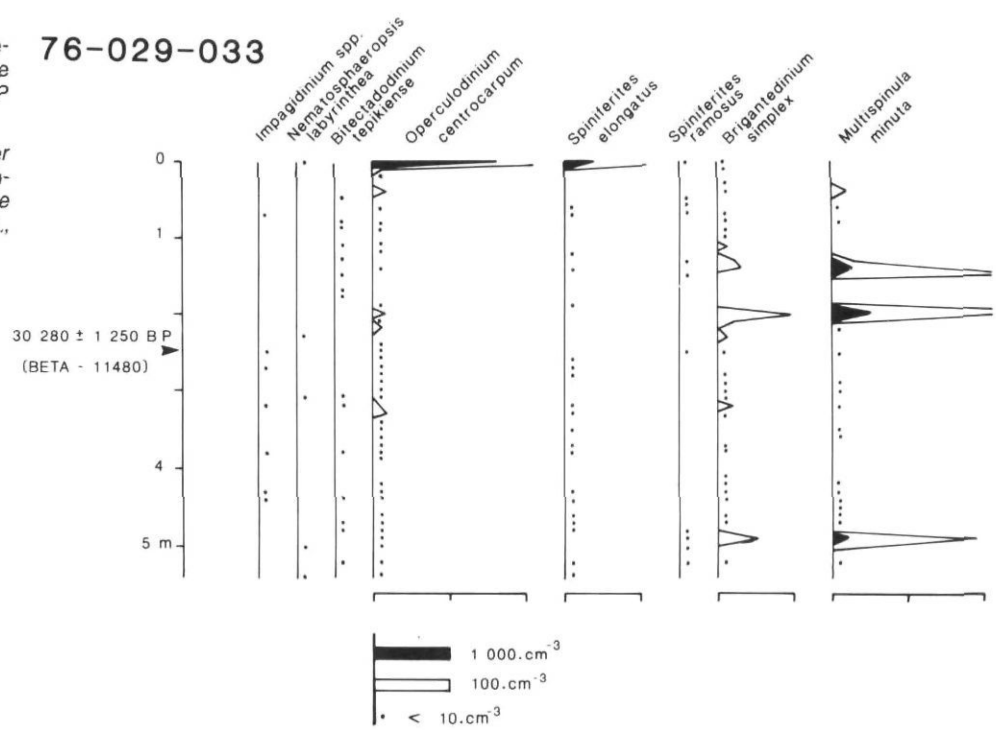


FIGURE 3F. Palynological record of Baffin Bay: dinoflagellate cyst record in core 79-029-033P (*cf.* de Vernal *et al.*, 1987).

La palynostratigraphie de la mer de Baffin: diagramme de concentration des dinokystes de la carotte 79-029-033P (cf. *de Vernal* et al., *1987).*



in the trigger weight core (TWC), which belongs to the present interglacial according to the $\delta^{18}O$ curve, is characterized by an abundant dinocyst microflora (up to 8000 cysts·cm^{-3}; Fig. 4A) dominated by *Nematosphaeropsis labyrinthea* and *Operculodinium centrocarpum* accompanied notably by *Spiniferites ramosus, Impagidinium sphaericum* and *Spiniferites elongatus* (Fig. 4B). Such an assemblage reflects relatively high primary productivity related to fully subarctic conditions in surface water masses. The isotopic stages 2/1 transition, which is well defined in both LCF and TWC cores (Fig. 2B), is marked by the dominance of *Brigantedinium simplex*, indicating low salinity in surface water masses (<30‰; Mudie and Short, 1985) as a response to meltwater transit through the West Greenland Current. The Late Pleistocene deposits contain a moderately rich dinocyst flora although the concentration varies (0 to 2000 cysts·cm^{-3}). Most assemblages are dominated by *Brigantedinium simplex*, which is accompanied in some cases by *Multispinula minuta*, suggesting

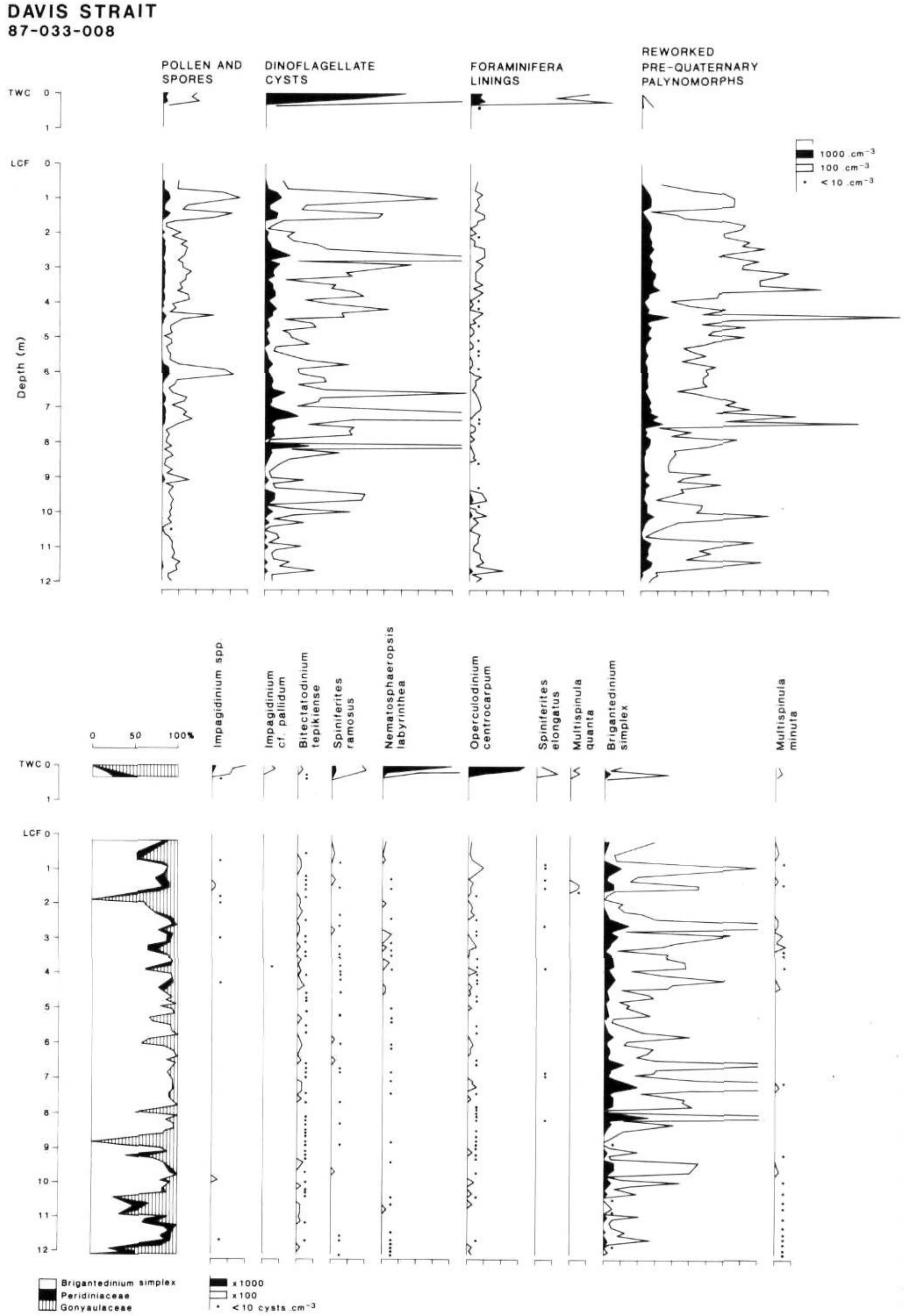


FIGURE 4. Palynological record in cores 87-033-008 TWC and LCF (data are first published herein): A. palynomorph concentrations; B. dinoflagellate cyst record.

Palynostratigraphie des carottes 87-033-008 TWC et LCF (données inédites): A. concentration des palynomorphes; B. diagramme de concentration des dinokystes.

meltwater runoff and Arctic type conditions. Also of note are the tenuous but significant occurrences of subarctic to cool temperate taxa such as *Operculodinium centrocarpum, Nematosphaeropsis labyrinthea, Spiniferites ramosus* and *Bitectatodinium tepikiense*, which are likely related to inputs from the North Atlantic Drift through the West Greenland current into the Labrador Sea during most of Late Pleistocene.

EASTERN LABRADOR SEA

In the eastern Labrador Sea, off southwest Greenland, the Late Pleistocene palynostratigraphy is well documented by studies on core HU-75-37 (de Vernal and Hillaire-Marcel, 1986, 1987b) and on a composite sequence from Site 646 (Aksu *et al.*, 1989). At both sites, the isotopic stage 1 may be distinguished by its rich dinocyst content (5000 to 30,000 cysts·cm^{-3}; Fig. 5A-B) and subarctic assemblages with *Operculodinium centrocarpum, Nematosphaeropsis labyrinthea, Spiniferites ramosus* and *S. elongatus* being dominant (Fig. 5C-D). A late glacial and early postglacial assemblage with upward decreasing *Brigantedinium* percentage may be distinguished. Most of the Late Pleistocene, including late isotopic stage 5 to isotopic stage 2, is characterized by moderate occurrences of subarctic-cool temperate taxa such as *Operculodinium centrocarpum*, *Bitectatodinium tepikiense* and *Nematosphaeropsis labyrinthea* and by episodic abundance peaks of *Brigantedinium simplex*. Continuous penetration of a branch of the North Atlantic Drift into the Labrador Sea and episodical meltwater runoff from southern Greenland may be deduced from the dinocyst record of stages 5 to 1. The last Interglacial (isotopic substage 5e) is present only in the composite record of Site 646 (Fig. 5D). It is marked by a particularly rich dinoflagellate cyst assemblage with abundant temperate taxa (*Spiniferites mirabilis* and *Bitectatodinium tepikiense*) in addition to the subarctic taxa which constitute the modern assemblages. Cool-temperate conditions in surface water masses, significantly warmer than present, therefore existed in the Labrador Sea during the last Interglacial, at least during the isotopic substage 5e. The stage 5 episode, however, cannot be easily subdivided on the basis of both dinocyst and $\delta^{18}O$ records at Site 646, in which the fully interglacial (sub-stage 5e) to glacial (stage 4) transition seems to be progressive rather than clearly tricyclical as may be expected.

The pollen and spore content in core HU-75-37 and in the composite sequence of Site 646 is relatively high allowing sufficient counting to establish conventional percentage diagrams with a few gaps (Fig. 5E-F). In core HU-75-37, which has been analyzed with a better resolution (sampling interval = 10 cm) than those of Site 646 (sampling interval = 20 cm), the pollen and spore stratigraphy led to direct correlation with the terrestrial palynostratigraphy of eastern Canada (*cf.* de Vernal et Hillaire-Marcel, 1987b). Notably, it has been possible

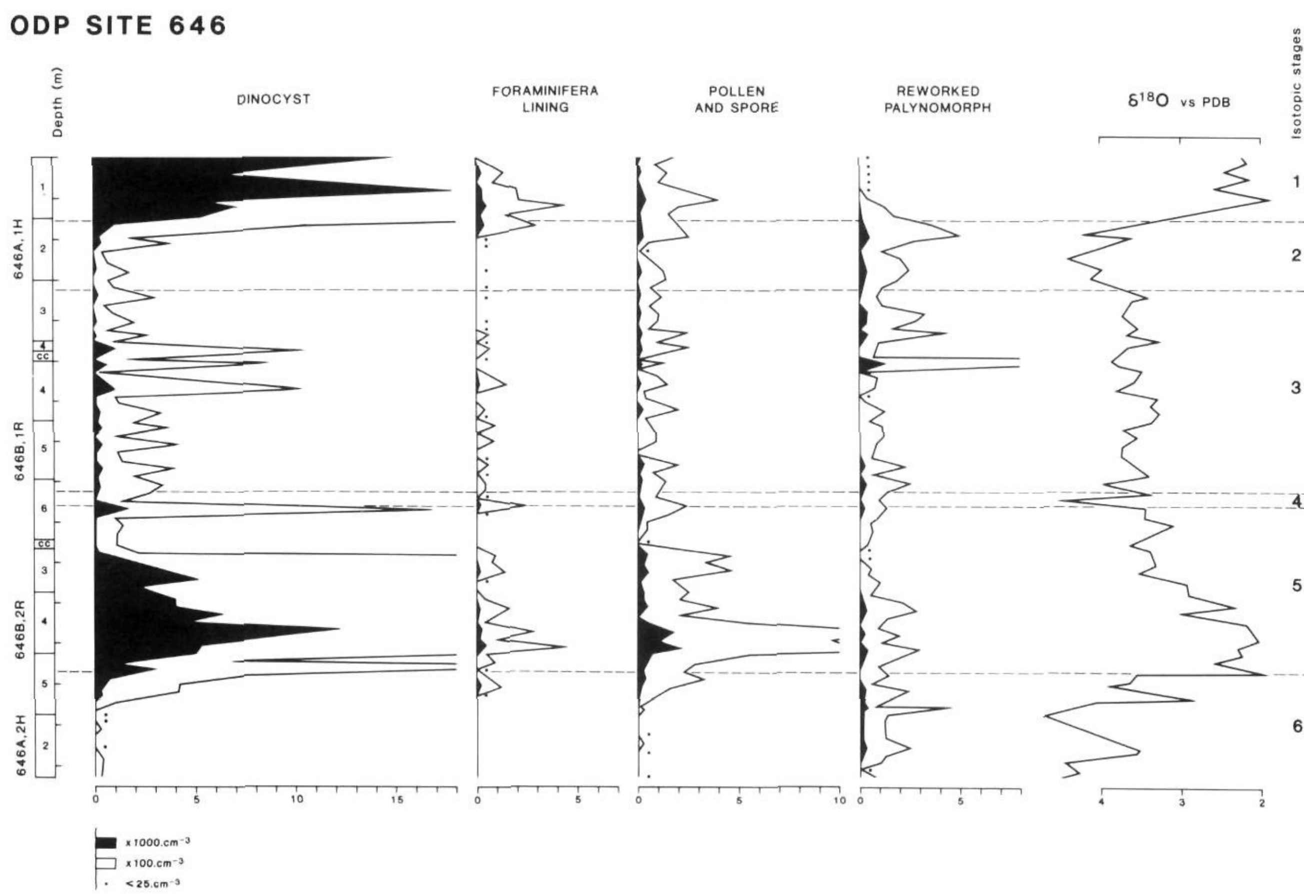


FIGURE 5A. Palynological record off southwest Greenland: palynomorph concentrations at Site 646 (*cf.* Aksu *et al.*, 1989).

Palynostratigraphie au sud-ouest du Groenland: concentration des palynomorphes au site 646 (cf. Aksu et al., *1989).*

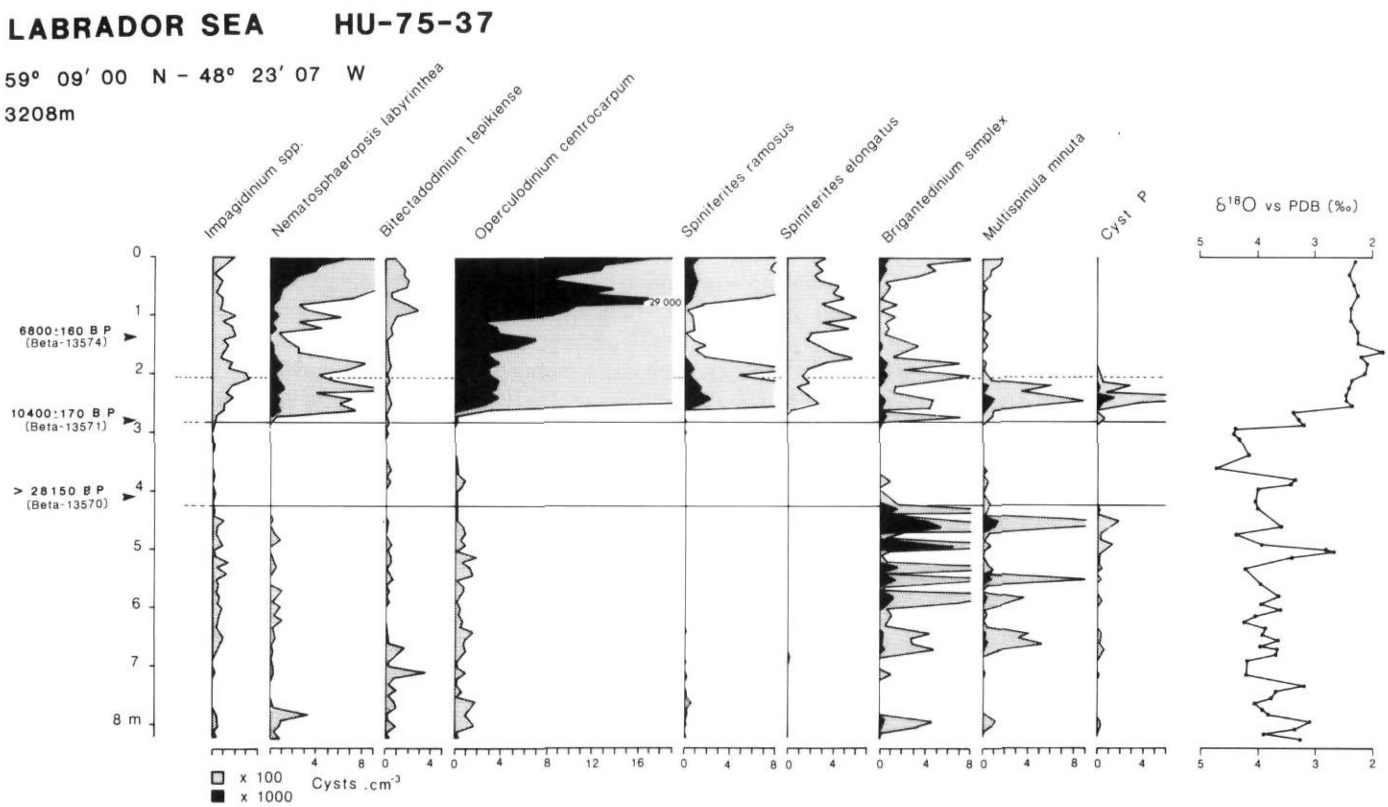


FIGURE 5B. Palynological record off southwest Greenland: palynomorph and coarse sand concentrations in core HU-75-37 (*cf.* de Vernal and Hillaire-Marcel, 1987b).

Palynostratigraphie au sud-ouest du Groenland: concentrations des palynomorphes et des sables grossiers dans la carotte HU-75-37 (cf. de Vernal et Hillaire-Marcel, 1987b).

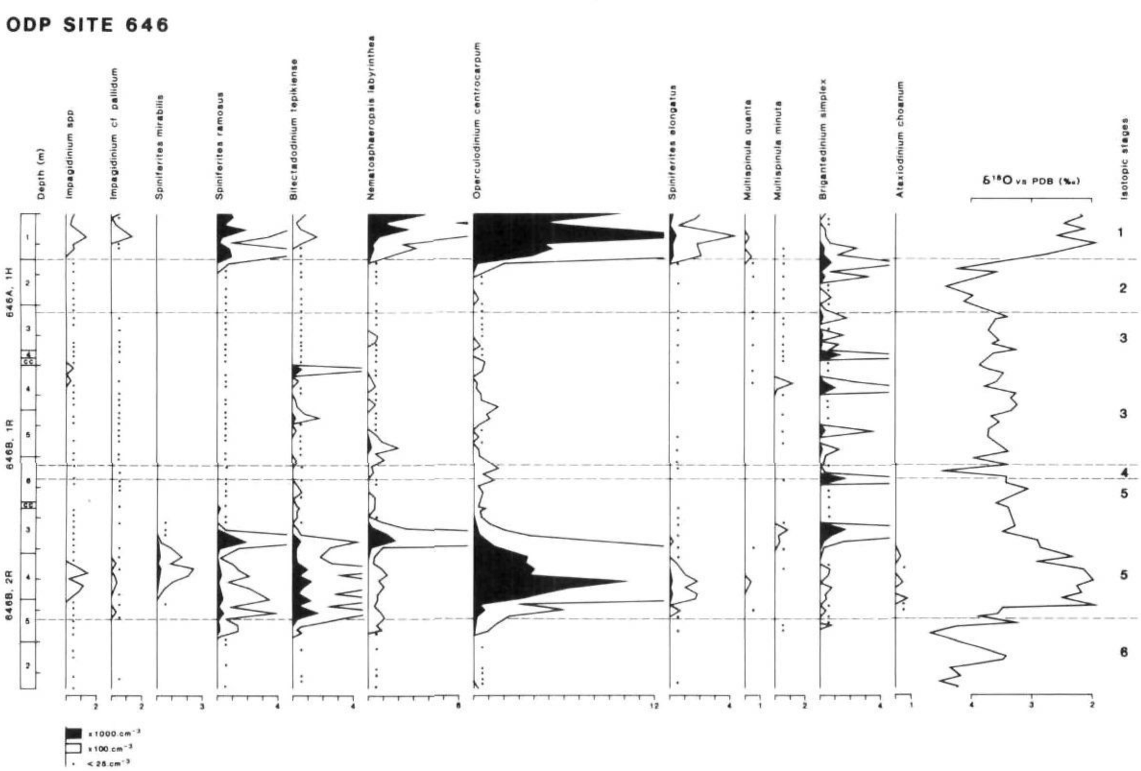


FIGURE 5C. Palynological record off southwest Greenland: summarized dinoflagellate cyst record in the composite sequence of Site 646 (*cf.* Aksu *et al.*, 1989).

Palynostratigraphie au sud-ouest du Groenland: diagramme résumé de la concentration des dinokystes dans la séquence composite du site 646 (cf. Aksu et al., 1989).

to correlate the postglacial record directly with the palynostratigraphy of southern Labrador (Lamb, 1980; Engstrom and Hansen, 1985) and to deduce influxes mainly controlled by WSW-ENE atmospheric transportation. Assuming a similar atmospheric circulation pattern over the Labrador Sea for the Late Pleistocene, the pollen and spore assemblages of core HU-75-37 indicate the existence of a shrub tundra vegetation along the southern Labrador coast and possibly over Newfoundland during the Middle Wisconsinan episode and a subsequent impoverishment of the vegetational cover during the Late Wisconsinan. At Site 646, the pollen and spore assemblages correlative of the last Interglacial are particularly rich with concentrations up to 2000·cm^{-3}, indicating fluxes from a dense vegetation. The assemblages, which are dominated by Pteridophyte spores (*Lycopodium* and *Osmunda*) and shrub taxa (*Betula* and *Alnus crispa*), however indicate the existence of non-forested vegetation in the main source area. Because the palynology of continental sedimentary sequences reveal the extension of dense mixed forests in Atlantic Canada during the Sangamonian (de Vernal *et al.*, 1986; Mott and Grant, 1986), correlation with the Site 646 palynostratigraphy cannot be established. Actually, the very high pollen and spore con-

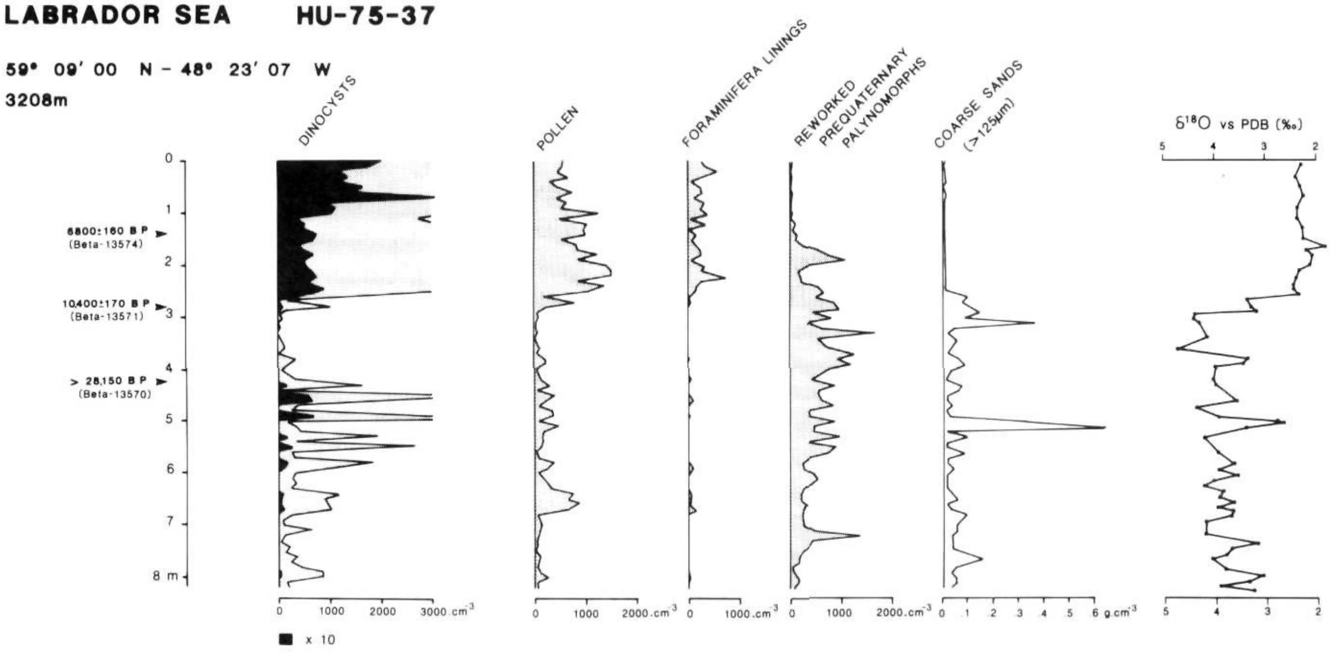


FIGURE 5D. Palynological record off southwest Greenland: summarized dinoflagellate cyst record in core HU-75-37 (*cf.* de Vernal and Hillaire-Marcel, 1987b).

*Palynostratigraphie au sud-ouest du Groenland: diagramme résumé de la concentration des dinokystes dans la carotte HU-75-37 (*cf.* de Vernal et Hillaire-Marcel, 1987b).*

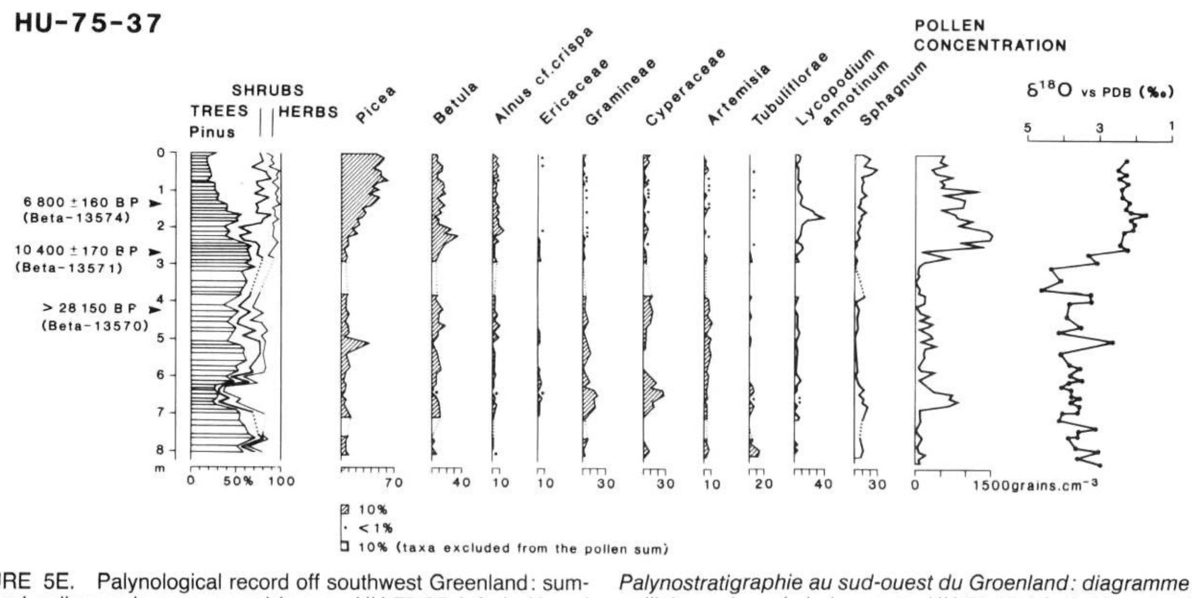


FIGURE 5E. Palynological record off southwest Greenland: summarized pollen and spore record in core HU-75-37 (*cf.* de Vernal and Hillaire-Marcel, 1987b).

*Palynostratigraphie au sud-ouest du Groenland: diagramme sporopollinique résumé de la carotte HU-75-37 (*cf.* de Vernal et Hillaire-Marcel, 1987b).*

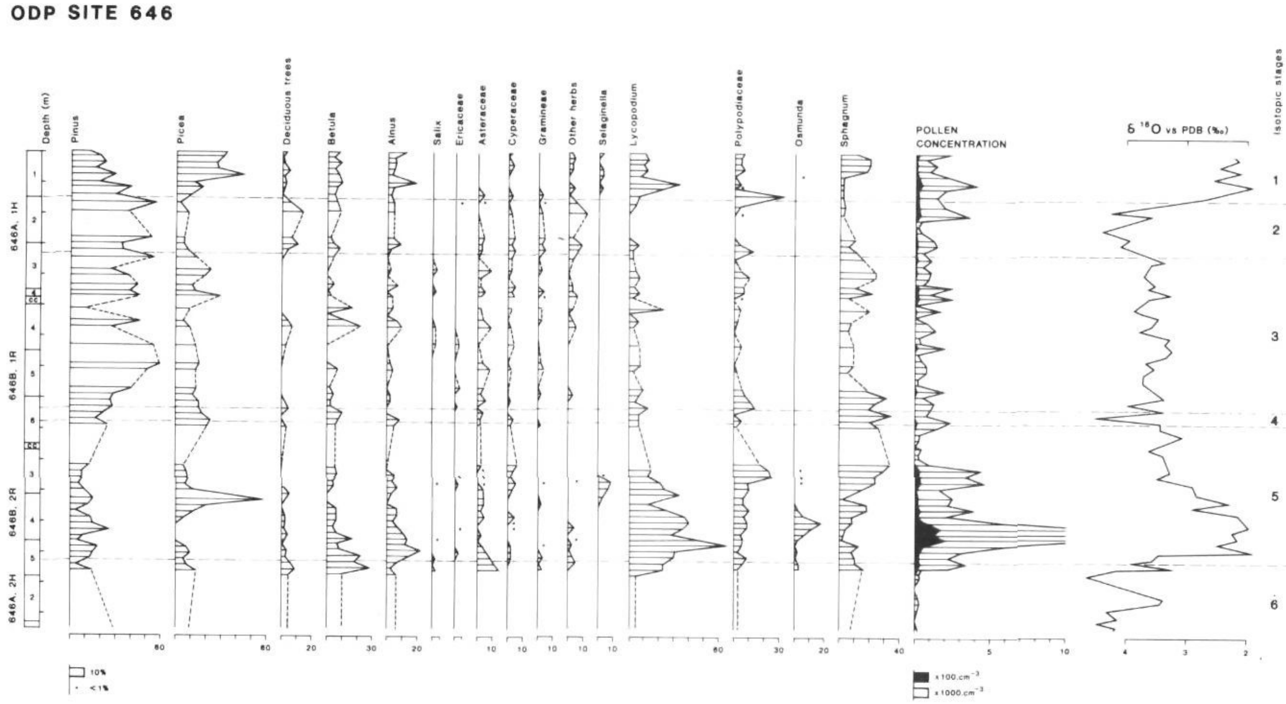


FIGURE 5F. Palynological record off southwest Greenland: summarized pollen and spore record in the composite sequence of Site 646 (*cf.* Aksu *et al.*, 1989). Pollen and spores are included in the sum.

*Palynostratigraphie au sud-ouest du Groenland: diagramme sporopollinique de la séquence composite du site 646 (*cf. *Aksu* et al., *1989). Le pollen et les spores sont inclus dans la somme.*

centrations recorded at Site 646 as well as the absence of correlation with the east Canadian palynostratigraphy strongly suggest that the last interglacial pollen and spore assemblages of Site 646 correspond to inputs from different sources: an atmospheric input from a southwest origin (see *Pinus* and deciduous tree curves) and a dominant input from a shrub tundra type vegetation. The latter may be attributed to fluvial input from south Greenland. If correct, this interpretation leads to the conclusion that large areas of southern Greenland were free of ice and occupied by a dense vegetation dominated by shrubs and pteridophytes, at least during the substage 5e interglacial. From a paleoclimatic viewpoint, the high percentages of *Osmunda* cf. *cinnamomea* (up to 20%) are very interesting. Indeed, this fern taxa grows in humid environments and has a northernmost modern limit of 51°N in eastern Canada (*cf.* Rousseau, 1974). The peak of *Osmunda* therefore suggests the existence of subarctic or even temperate climates in the source area, which is apparently located in southern Greenland. Such a climate is favorable to forest development, which may have been limited on Greenland because of the insular context, unconducive for rapid tree migration. At Site 646, strong changes in pollen and spore assemblages are recorded in the upper part of the isotopic stage 5: decrease in concentration and increasing *Picea* percentages. This trend suggests a drop of inputs from Greenland and a restoration of influxes from eastern Canada mainly controlled by the atmospheric circulation. The assemblages would mainly reflect the existence of coniferous boreal forest to tundra forest in eastern Canada during a part of the last Interglacial (isotopic substages 5d to 5a?), while a diminution of the vegetation cover on Greenland due to significant ice growth probably explain the drop recorded in concentrations.

WESTERN LABRADOR SEA

Core 84-030-021 constitutes the only sedimentary sequence from the continental rise off Labrador spanning the last glacial maximum to Recent, *i.e.* isotopic stages 2 and 1 (Fig. 6A). Partly correlative palynostratigraphy is also available for the central Labrador shelf (Mudie, 1980).

The dinoflagellate cysts assemblages (Fig. 6B) of the isotopic stage 2 are generally dominated by *Brigantedinium simplex*, suggesting a dilution in surface water masses (salinity $< 30‰$; Mudie and Short, 1985), as also deduced from the relatively light $\delta^{18}O$ values. A peak of the temperate taxa *Bitectatodinium tepikiense* correlative with an ^{18}O-depleted phase is recorded shortly after *ca.* 17,000 BP, suggesting an early melting event likely related to a brief but significant climatic warming at high latitudes. In the dinocyst record, the transition from the glacial assemblage dominated by *Brigantedinium simplex* to the modern subarctic assemblage with abundant *Nematosphaeropsis labyrinthea* and *Operculodinium centrocarpum* is progressive from ~ 11,000 BP to ~ 4000 BP. The settlement of fully interglacial condition appears therefore to be later in western Labrador Sea than in the eastern part of the basin.

The pollen and spores assemblages (Fig. 6C) of the stage 2 interval are characterized by the dominance of *Pinus, Picea* and *Asteraceae* indicating inputs from an open coniferous forest vegetation likely located at the southern margin of the

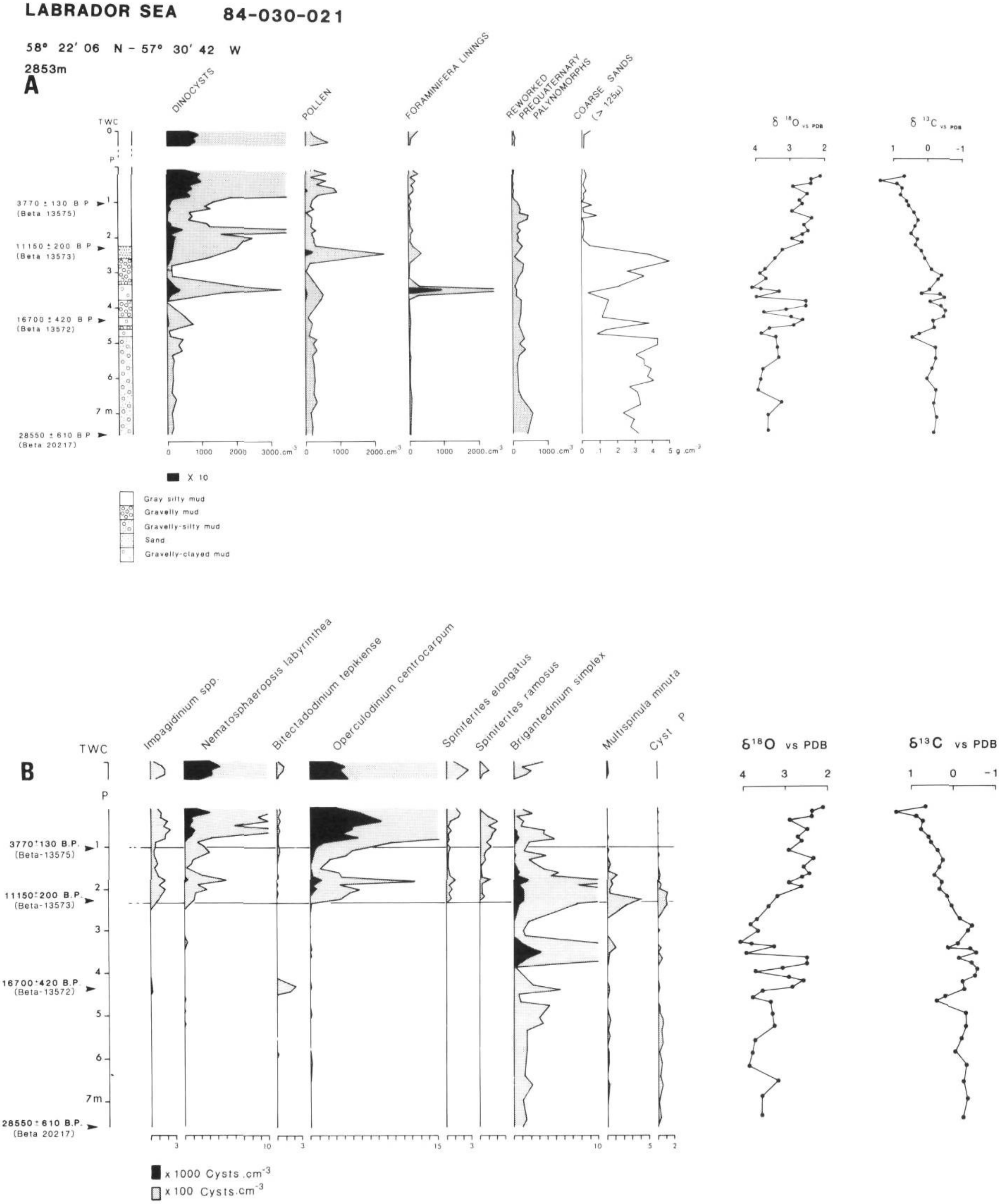


FIGURE 6 A and B. Palynological record in cores 84-030-021 TWC & P (data summarized from de Vernal and Hillaire-Marcel, 1987b). A. Lithostratigraphy, palynomorph and coarse sand concentrations; B. dinoflagellate cyst record.

Palynostratigraphie des carottes 84-030-021 TWC et P (les données de Vernal et Hillaire-Marcel, 1987b, sont ici simplifiées): A. lithostratigraphie, concentration des palynomorphes et des sables grossiers; B. diagramme de concentration des dinokystes.

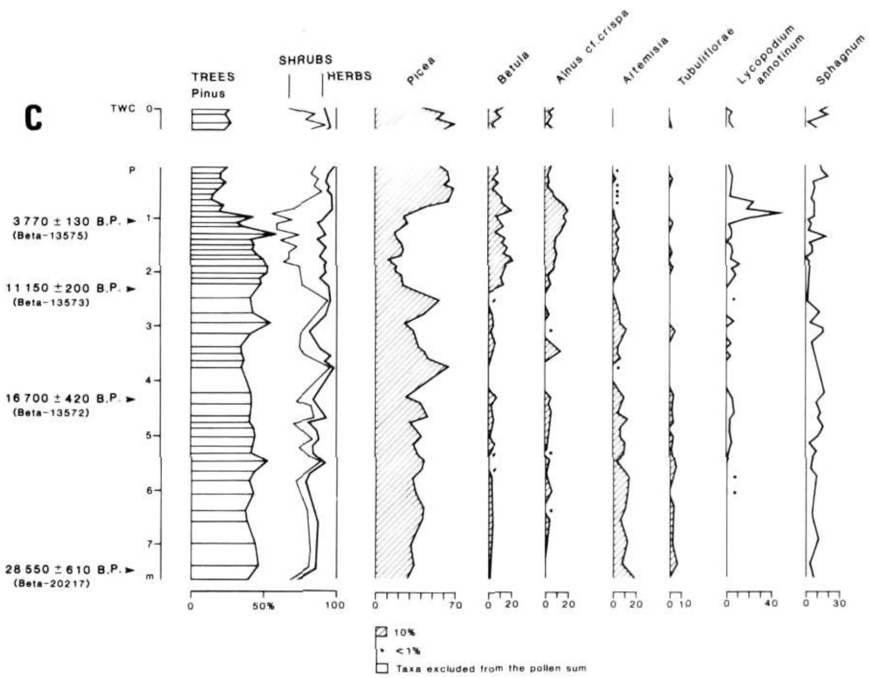


Figure 6C. Palynological record in cores 84-030-021 TWC & P (data summarized from de Vernal and Hillaire-Marcel, 1987b). Pollen and spore record.

Palynostratigraphie des carottes 84-030-021 TWC et P (les données de Vernal et Hillaire-Marcel, 1987b, sont ici simplifiées). Diagramme sporopollinique.

Laurentide Ice Sheet. These inputs apparently related to the advection of air masses coming from the southern Laurentide ice margin with a circulation pattern controlled by pressure and temperature gradients, as already suggested on theoretical ground by Ruddiman and McIntyre (1981). The postglacial pollen assemblages, which allows direct correlations with the continental palynostratigraphy of northern Labrador (*e.g.* Short and Nichols, 1977), suggest influxes mainly controlled by WSW-ENE air mass trajectories similar to present.

THE SOUTH CENTRAL LABRADOR SEA

Dinoflagellate cyst assemblages in cores 84-030-003TWC and P are characterized by low concentrations (100-500 cysts·cm^{-3}) or fluxes (0.5 to 3 cysts·cm^{-2}·yr^{-1}; Fig. 7A) although the taxonomic diversity is high, including subtropical to arctic taxa, throughout the sequence. The local dinoflagellate cyst production was low, probably because of the offshore location of the site that account for limited nutrients, and the mixed character of the assemblage seems to primarily reflect a transportation through both the Labrador Current and the North Atlantic Drift Current (*cf.* de Vernal, 1986; de Vernal and Hillaire-Marcel, 1987b-c). The data summarized in Figure 7A suggest the following points: (1) a continuous penetration of a westward branch of the North Atlantic Drift into the Labrador Sea throughout the Late Pleistocene; (2) a fluctuating productivity off eastern Canada, with minimums being recorded during the isotopic stages 6 and 2. The noticeable occurrence of *Spiniferites mirabilis* (*cf.* de Vernal and Hillaire-Marcel, 1987c) in deposits correlated with isotopic substage 5e tends to confirm temperate conditions in surface water masses off eastern Canada during the last Interglacial. The dominance of *Bitectatodinium tepikiense* in the entire stage 5, with the exception of a brief interval overlapping and following the substage 5d, suggests that cool-temperate conditions prevailed off eastern Canada from the Sangamonian *s.s.* to the Early Wisconsinan.

The general paucity of the pollen and spore assemblages in core 84-030-003 and the dominance of *Pinus* (Fig. 7B) indicate very long distance inputs controlled by SW-NE or SSW-NNE air mass trajectories throughout the Late Pleistocene.

CONTINENTAL POLLEN RECORDS

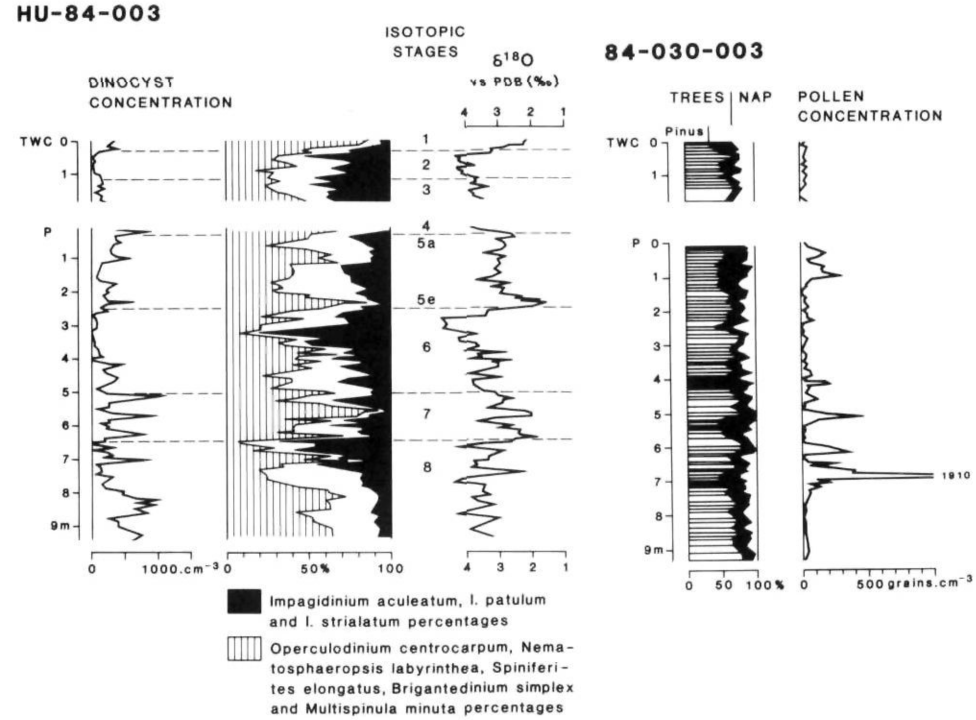
As mentioned earlier in this paper, most continental sedimentary sequences from eastern Canada show fragmentary records of the Late Pleistocene. Their systematic study with special emphasis on a palynological approach by Mott since the early seventies and later on by de Vernal and Mott allowed the recognition of three very distinct palynostratigraphic units (*e.g.* de Vernal and Mott, 1986). These have however never been observed in a complete stratigraphical sequence[1] including at the reference section of East Bay (*ibid.*; Fig. 8) where all units are present, but at the favour of sediments collapsed in a depression of karstic origin which do not show clear stratigraphic relationships. When combining records where two of these palynostratigraphic units are seen in succession, the sequential occurrence of the three is ascertained (*cf.* de Vernal and Hillaire-Marcel, 1987a).

Absolute time controls cannot be obtained from ^{14}C measurements: all wood and peat remains of these units yielded "infinite" ages or very low activities (<2% of "modern" carbon; *ibid.*); most of them can barely be translated into "true" ages. Aminoacid analyses of wood fragments by Occhietti and Rutter (1982) revealed largely spread racemization rates within each

1. A high-resolution seismic survey by the CSS-Dawson (HU-85-036; D. Piper, chief scientist) in Lake Bras d'Or (Cape Breton Island) revealed a very thick, well stratified sequence in St. Andrews Channel that may likely yield a relatively complete record of the Late Pleistocene. A drilling operation is planned but technical difficulties have to be solved first.

FIGURE 7. Palynological record in cores 84-030-003 TWC & P (data summarized from de Vernal and Hillaire-Marcel, 1987b,c). A summarized dinoflagellate cyst record; B. summarized pollen record.

Palynostratigraphie des carottes 84-030-003 TWC et P (données tirées de Vernal et Hillaire-Marcel, 1987b, c) : A. diagramme simplifié des assemblages de dinokystes; B. diagramme pollinique résumé.



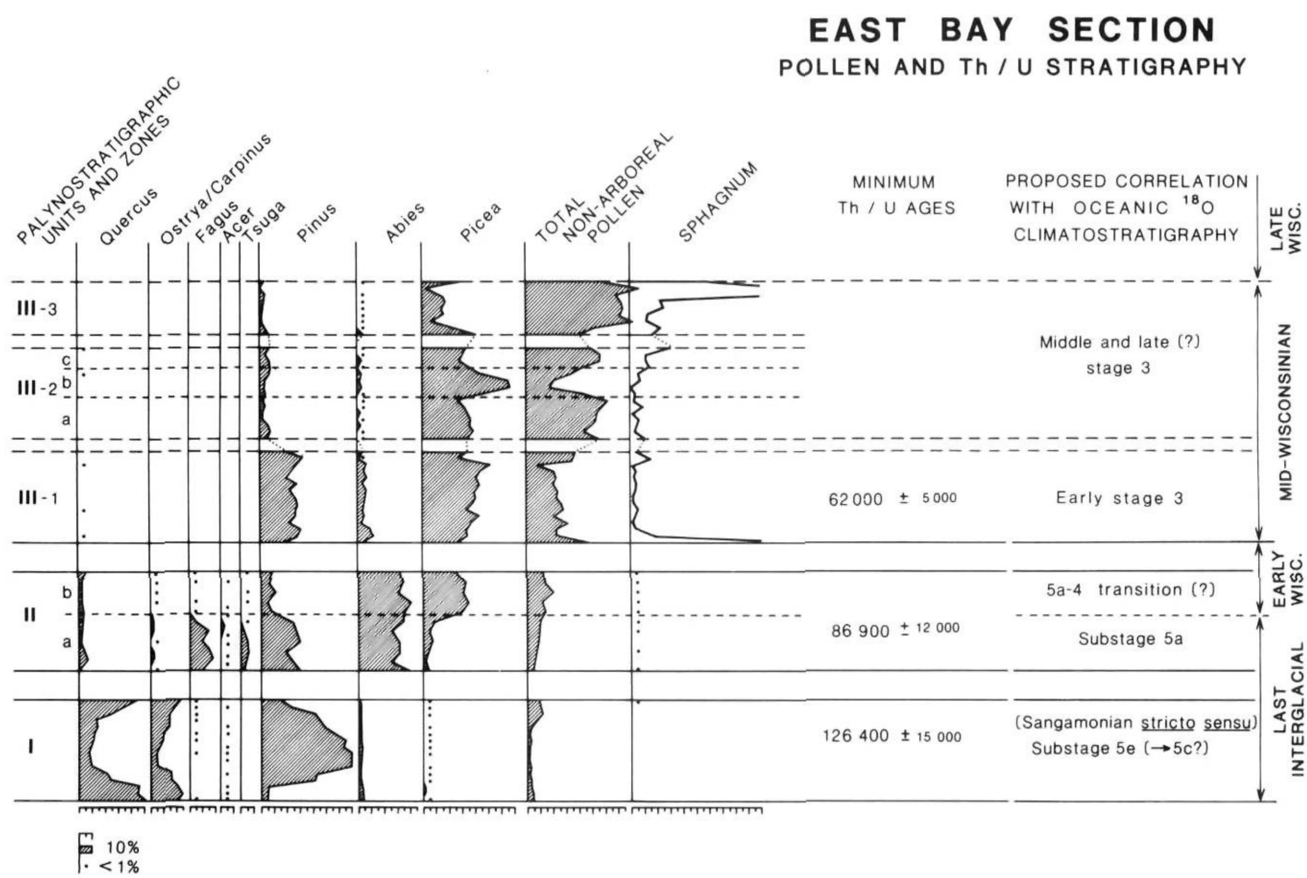


FIGURE 8. Summarized Late Pleistocene palynostratigraphy and chronostratigraphy of the East Bay section (from de Vernal *et al.*, 1986).

Représentation schématique de la palynostratigraphie et de la chronostratigraphie du Pléistocène supérieur de la coupe d'East Bay (tirée de Vernal et al.*, 1986).*

unit; they pointed to the irrelevance of chronological assessments from such data. Until now, the most successful approach with respect to "absolute" dating of these units is the Th/U disequilibrium method (*cf.* de Vernal *et al.*, 1986; Causse and Hillaire-Marcel, 1986). Inasmuch as Th/U data on fossil wood are essential for setting a chronostratigraphy on these on-land sequences, minimum information is given below.

Th/U CHRONOLOGY

The Th/U disequilibrium method (Goldberg and Koide, 1962) has been successfully applied to the dating of organic matter (*e.g.* Vogel and Kronfeld, 1980) when a "closed" radioactive system has prevailed since burial. Unfortunately, such ideal conditions are rarely encountered, and this statement is valid with respect to Atlantic Canada fossil wood but it can be generalized for most continental environments and deposits (Hillaire-Marcel and Causse, 1989a-b; Hillaire-Marcel *et al.*, 1988). Hence it is essential to evaluate the degree of closure of the radioactive system.

A very poor closure of the radioactive system is commonly observed in highly porous material, such as gravels and peat, where intense water circulation results in continuous migration of uranium into wood remains. Several indicators of such a process exist: (1) an inverse relationship between U concentrations and $^{230}Th/^{234}U$ ratios in contemporaneous samples, (2) highly variable $^{234}U/^{238}U$ activity ratios in nearby samples, (3) a significant presence of ^{232}Th in the samples (being strictly of "detrital" origin, the latter indicates incorporation of fine detrital particles into the sample), (4) a $^{228}Th/^{232}Th$ disequilibrium (*cf.* Hillaire-Marcel and Causse, 1989a), to mention just a few criteria.

In low-porosity and water-saturated sediments with moderate hydraulic gradients, relatively "closed" systems are observed (*cf.* Causse and Hillaire-Marcel, 1986). Evidence of this is found in consistent U & Th concentrations and activity ratios in samples from a single unit, and also in the relative coherence of comparative sets of data from overlying or underlying units.

Both situations were encountered when analysing samples from each palynostratigraphic unit from the sections mentioned previously. Unit 1, particularly at East Bay, shows evidence of resumption of U-uptake by a few samples after the usual post-depositional early phase of U-uptake. Nevertheless, all samples analysed fit into one single isochron (Fig. 9A; *cf.* de Vernal *et al.*, 1986) that yields an age of *ca.* 120,000 yrs. The latter is minimum in view of what precedes. The relative coherence of the whole set of data and the age obtained for the immediately overlying unit II (see below) suggest that the "true" age of unit I should not be really much older: an assignment of unit I to the climatic optimum (isotopic substage 5e) of the last Interglacial seems therefore reasonable.

As seen in Figure 9B, the three samples assigned to unit II fit into one single isochron that corresponds to an age of *ca.* 85,000 yrs. An assignment of this unit to the isotopic substage 5a is suggested.

Unit III yielded very few wood fragments suitable for Th/U measurements. Moreover, this unit spans over a relatively long period of time (*cf.* de Vernal and Mott, 1986): there is no reason to believe that these wood remains are contemporaneous. Two "minimum" ages were however obtained: 62,000 ± 5,000 yrs at East Bay and 47,000 ± 5,000 at Bay St. Lawrence (de Vernal *et al.*, 1983, 1986). Both would support the assignment of this unit to the Middle Wisconsinan, *i.e.* the isotopic stage 3.

PRE-LATE PLEISTOCENE RECORD

At Le Bassin, on the Îles de la Madeleine, the palynological record (Fig. 10A; Mott and Grant, 1986) shows, underlying a sequence assigned to palynostratigraphic unit I (see below), a palynological assemblage that is likely illustrative of the Illinoian/Sangamonian transition (*i.e.* transition 6/5e). It corresponds to an open tundra/forest vegetation indicative of periglacial conditions. The whole sequence is thought to represent the climatic shift from late glacial to full interglacial conditions. In parallel, changes are observed in the composition of the aquatic microflora: the fresh-water *Pediastrum* flora is replaced by assemblages of marine dinocysts that are present up to *ca.* 1.4 m above mean sea level. This sedimentary sequence may therefore illustrate the marine transgression of the last Interglacial.

PALYNOSTRATIGRAPHICAL UNIT I

Palynostratigraphical unit I is observed at East Bay (Fig. 8), Le Bassin (Fig. 10A; de Vernal and Mott, 1986), Addington Forks (Fig. 10B; Mott and Grant, 1986), and at Green Point (*cf.* Mott and Grant, 1986). It is characterized by the dominance

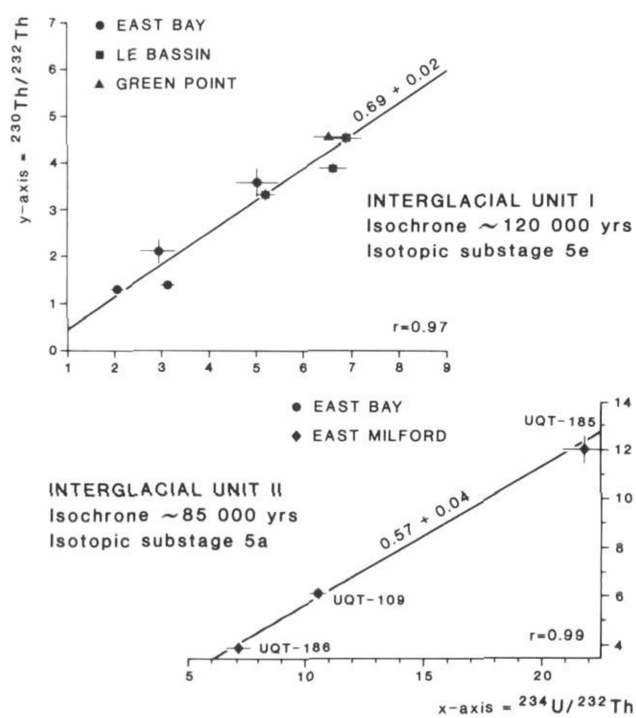


FIGURE 9. Th/U Isochrons from units I (A) and II (B) (*cf.* Hillaire-Marcel and Causse, 1989b).

Isochrones Th/U des unités I (A) et II (B) (cf. *Hillaire-Marcel et Causse, 1989b).*

of *Quercus*, *Ostrya/Carpinus* type and of *Pinus* cf. *strobus*. At East Bay notably, these taxa (*Quercus* cf. *rubra, Ostrya*, and *P. strobus*) also occur as macrofossils (de Vernal and Mott, 1986). Unit I suggests closed forests dominated by thermophilous trees and a climate warmer and dryer than that of today. For comparison purposes, it should be mentioned that pollen percentages of *Quercus* as high as those measured in unit I (20 to 50%) are reported for modern pollen spectra from the more southern dense deciduous forest of New England (*e.g.* Davis and Webb, 1975; Delcourt *et al.*, 1984). Clearly, unit I represents full interglacial conditions: those of the Sangamonian *stricto sensu* (isotopic substage 5e) as also suggested by its Th/U age (Fig. 9A).

PALYNOSTRATIGRAPHICAL UNIT II

This unit is well represented at East Bay (Fig. 8), at East Milford with minor differences (Fig. 10C; *cf.* Mott *et al.*, 1982; de Vernal and Hillaire-Marcel, 1987a), and also at Addington Forks (Fig. 10B) where interestingly enough it apparently succeeds the former unit I without discontinuity. At East Bay, unit II is characterized by high percentages of *Abies balsamea*, which is also present as a macrofossil along with *Tsuga canadensis* and *Picea*. At the base, in sub-unit IIa, *Abies balsamea* is mainly associated with *Pinus* sp., *Fagus grandifolia*, and *Tsuga canadensis*, indicating the presence of a mixed forest dominated by fir, beech, hemlock, pine and spruce. A cool and wet climate, somewhat comparable to the present one, may be inferred from this assemblage. Above, in sub-unit IIb, the most thermophilous pollen taxa decrease, whereas *Picea* values increase. This suggests an impoverishment of the forest cover and the expansion of a predominantly coniferous forest. Sub-unit IIb would be therefore indicative of a climatic cooling. At East Milford, a somewhat similar succession is observed although the drop in thermophilous pollen taxa is more pronounced. To a certain extent, the top assemblages of the East Milford diagram are intermediate between those of the above sub-unit IIb and those of unit III, which is discussed below.

Assignment of unit II to a "warm" substage (5c or 5a) of the isotopic stage 5 seems reasonable from a paleoclimatic point of view. Th/U measurements on fossil wood from this unit at East Milford and East Bay converge towards a probable age of *ca.* 85,000 yrs, which would fall into isotopic substage 5a. Then the cooling trend recorded by the transition from unit IIa to IIb could well be that of stage 5a/4 transition. If this is right, there is still one puzzling question unanswered: where is substage 5c? Since all the sedimentary sequences we have looked at here are discontinuous, it would be hazardous to hypothesize further.

PALYNOSTRATIGRAPHICAL UNIT III

This unit is by far the best preserved of the continental sedimentary sequences from Atlantic Canada. It has been reported in more than a dozen sites (*cf.* de Vernal and Hillaire-Marcel, 1987a for a review). Four of them yielded "finite" ^{14}C ages ranging from *ca.* 32,000 BP to *ca.* 44,000 BP, most others yielded "greater than" ages. The two Th/U measurements performed also point towards a "Middle Wisconsinan" age for this unit.

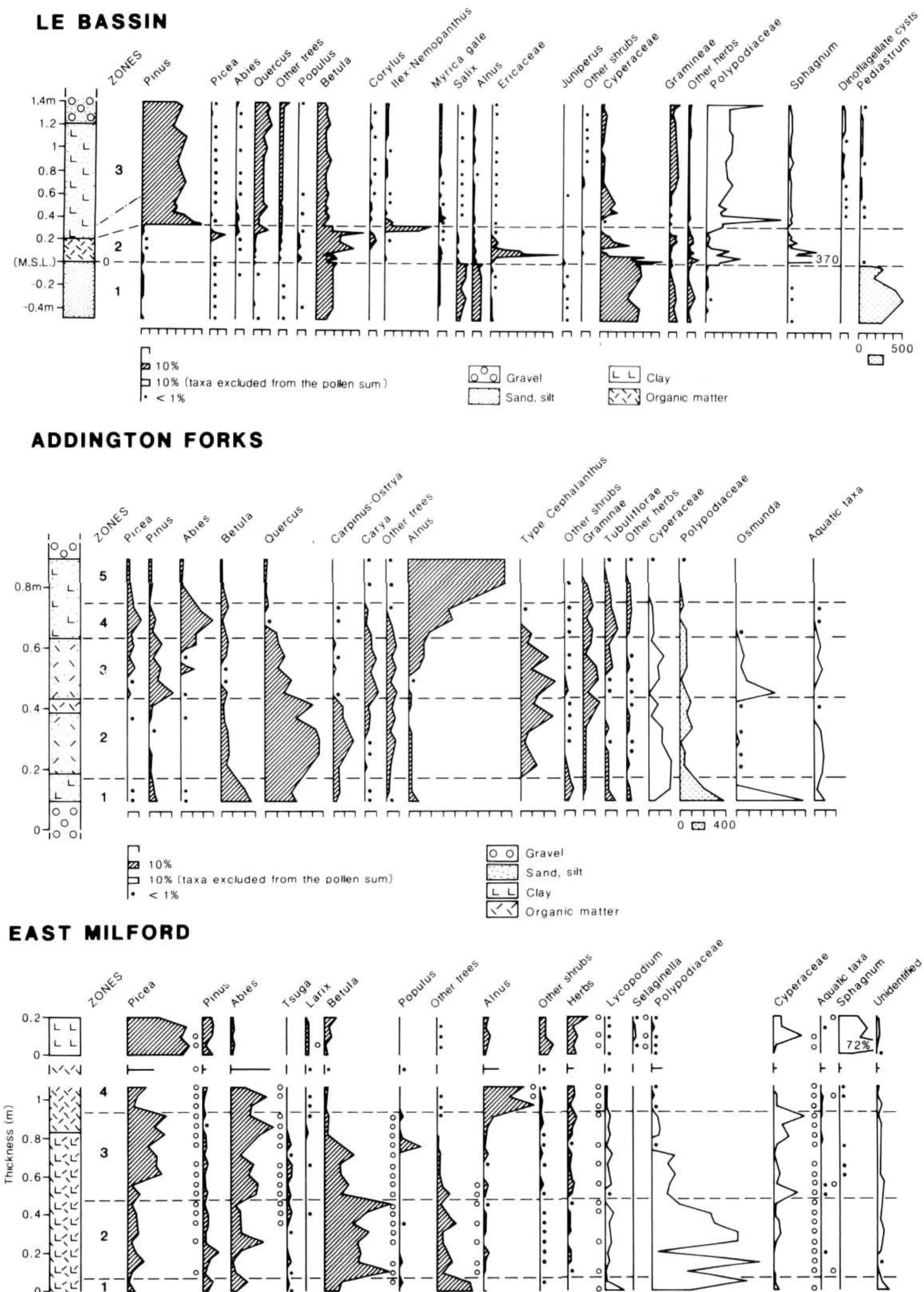
Unit III succeeds the two former ones at East Bay (Fig. 6B). It is better exposed nearby at Castle Bay (Fig. 10D; de Vernal and Mott, 1986). It shows a recurring succession of coniferous boreal forest/forest-tundra assemblages. The arboreal pollen content is characterized by a dominance of *Picea, Pinus* and *Abies*. Shrub pollen of *Alnus, Salix* and *Ericaceae* as well as herb pollen and spores of *Sphagnum* are present in relatively high but variable percentages. The arboreal pollen/total pollen (AP/T) percentage fluctuates from 30 to 80%. It indicates significant changes in the density of the forest cover that was occasionally replaced by a tundra-like vegetation. In this sequence that culminates some 20 m above mean sea level, several horizons contain marine dinocysts (mostly *Operculodinium centrocarpum* and *Spiniferites* sp). Lortie et *al.* (1984) also identified correlative marine diatom assemblages that alternate with a fresh-water diatom flora. The high relative sea levels recorded there are due to glacio-isostatic adjustments, which suggests nearby significant ice cover.

At Castle Bay, very high pollen concentrations are found (*ca.* 10^5 grains.cm^{-3}). Since unit III is observed throughout a *ca.* 15 m sequence, and because it depicts three moderate-amplitude vegetational shifts (boreal forest to tundra) and significant sea level oscillations, it certainly represents a relatively long period of sedimentation. Theoretical influx would account for a *ca.* 30,000 yr episode (*cf.* de Vernal and Mott, 1986). Unit III probably spans over a large part of the Middle Wisconsinan, *i.e.* of isotopic stage 3, as also suggested from Th/U measurement on wood at East Bay (Fig. 8) and Bay St. Lawrence (Fig. 10E) yielding ages of *ca.* 62,000 and 47,000 years respectively. We have seen previously that stage 3 is characterized by large fluctuations in the ^{18}O-records. The cyclic trend observed at Castle Bay (Fig. 10D) and Bay St. Lawrence (Fig. 10E) could well be the expression of these fluctuations at the southeastern margin of the Wisconsinan ice cover.

Since there is no till that can be definitely assigned to the Early Wisconsinan in the Castle Bay-East Bay area, we may also reasonably hypothesize that during isotopic stage 4, ice marginal conditions similar to those inferred from some of the sub-units III prevailed. Therefore, the latter may well be representative of most of the Early and Middle Wisconsinan periods at the southeastern edge of the country.

DISCUSSION

This overview of the Late Pleistocene records from eastern Canada and adjacent basins, with special emphasis on isotopic and palynological data, does not allow detailed paleogeographical reconstitutions for each glacial/interglacial or interstadial episode. From this viewpoint, we still have to document our records better: the CLIMAP group (1976), which addressed specifically the paleogeography of the last ice maximum from a much denser set of data finally produced two models, a "minimum"one and a "maximum" one showing drastic differences. The data presented here however make it possible to put some constraints on the ice budget and climate of


LE BASSIN
ZONES
Pinus
Picea
Abies
Quercus
Other trees
Populus
Betula
Corylus
Ilex-Nemopanthus
Myrica gale
Salix
Alnus
Ericaceae
Juniperus
Other shrubs
Cyperaceae
Gramineae
Other herbs
Polypodiaceae
Sphagnum
Dinoflagellate cysts
Pediastrum
1.4m
1.2
1
0.8
0.6
0.4
0.2
(M.S.L.) 0
-0.2
-0.4m
3
2
1
370
0
500
10%
10% (taxa excluded from the pollen sum)
< 1%
Gravel
Sand, silt
Clay
Organic matter
ADDINGTON FORKS
ZONES
Picea
Pinus
Abies
Betula
Quercus
Carpinus-Ostrya
Carya
Other trees
Alnus
Type Cephalanthus
Other shrubs
Graminae
Tubuliflorae
Other herbs
Cyperaceae
Polypodiaceae
Osmunda
Aquatic taxa
0.8m
0.6
0.4
0.2
0
5
4
3
2
1
0
400
10%
10% (taxa excluded from the pollen sum)
< 1%
Gravel
Sand, silt
Clay
Organic matter
EAST MILFORD
ZONES
Picea
Pinus
Abies
Tsuga
Larix
Betula
Populus
Other trees
Alnus
Other shrubs
Herbs
Lycopodium
Selaginella
Polypodiaceae
Cyperaceae
Aquatic taxa
Sphagnum
Unidentified
72%
Thickness (m)
0.2
0
1
0.8
0.6
0.4
0.2
0
4
3
2
1
10%
10% (taxa excluded from the pollen sum)
< 1%
Clay
Organic matter
Macrofossil occurrences

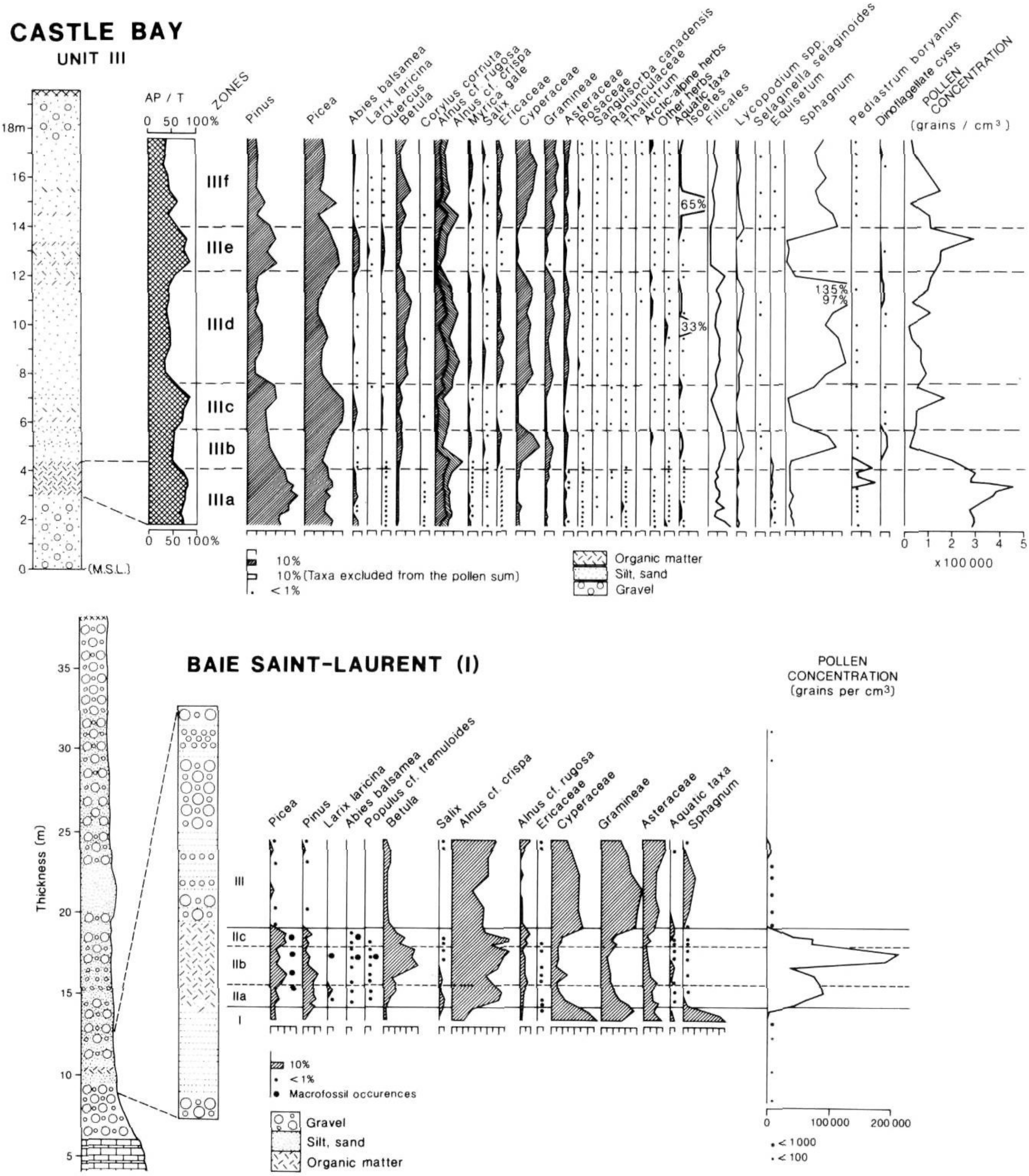


FIGURE 10. Palynostratigraphy of Atlantic Canada with some representative diagrams: A. Le Bassin section (from Mott and Grant, 1986); B. Addington Forks section (from Mott and Grant, 1986); C. East Milford section (from Mott *et al.*, 1982; D. Castle Bay section (de Vernal and Mott, 1986); E. Bay St. Lawrence section (de Vernal *et al.*, 1983).

Palynostratigraphie des provinces de l'Atlantique: quelques diagrammes représentatifs du Pléistocène supérieur: A. Le Bassin (cf. Mott et Grant, 1986); B. Addington Forks (cf. Mott et Grant, 1986); C. East Milford (cf. Mott et al., 1982; D. Castle Bay (cf. de Vernal and Mott, 1986); E. Baie Saint-Laurent (cf. *de Vernal* et al., *1983).*

some episodes of the last climatic cycle. They are discussed below with reference to the ^{18}O stratigraphy and summarized in Table I.

STAGE 6/5 TRANSITION

A 2.5 to 3‰ shift in records from the Labrador Sea at the 6/5 transition points toward a rapid disappearance of the Illinoian ice. From the mean sedimentation rates observed at sites 646 (~0.1 mm.yr^{-1}) and 647 (~0.05 mm.yr^{-1}), a *ca.* 10,000 yrs episode can be inferred. All records also show "heavier" $\delta^{18}O$ values in stage 6 than in stage 2. The Illinoian ice probably[2] had a larger volume than that of the Late Wisconsinan ice maximum. It seems likely that some of the southernmost tills of Canada assigned to Laurentide ice were deposited during the Illinoian maximum: the so-called "redflood" (copyright V. K. Prest) with reference to the color of the tills [*e.g.* the Bécancour Till (Gadd, 1971), the Johnville Till (McDonald and Shilts, 1971), the Sissiboo Dam lower till (Grant, 1980), the York Till\Don Formation (Terasmae, 1960)] of the Illinoian.

The climatic shift that led to the last Interglacial climatic optimum is illustrated on land by the transitional palynological sequence of Le Bassin, which shows similarities with the postglacial sequences observed notably by Mott *et al.* (1986).

ISOTOPIC SUBSTAGE 5e

The last Interglacial *stricto sensu* (*i.e.* isotopic substage 5e) shows systematic departure from the so-called "climatic optimum" of the Holocene (*cf.*, CLIMAP, 1984). Offshore, lighter $\delta^{18}O$ values are found in planktonic foraminifers pointing towards warmer and/or more diluted surface waters. Both the Labrador Sea and the Baffin Bay dinocyst assemblages were more diversified during substage 5e than during stage 1. In the Labrador Sea, in addition to a temperate-subarctic assemblage not unlike the modern one (*cf.* Aksu *et al.*, 1989), a noticeable occurrence of temperate taxa such as *Bitectatodinium tepikiense* and *Spiniferites mirabilis* is seen, whereas full subarctic conditions are inferred at the same time in Baffin Bay, where *Operculodinium centrocarpum* and *Spiniferites elongatus* are dominant. At that time, significant development of a shrub-tundra vegetation, probably over Baffin Island and possibly over Greenland, is indicated by pollen and spore spectra from substage 5e, at sites 645 and 646, which also give evidence of a northward shift of the boreal forest limit (*cf.* Mudie, 1982; de Vernal, 1986).

More to the south in the Atlantic Provinces, warmer (and dryer?) conditions than at present are also shown by a northward shift of the dense deciduous forest that today characterizes New England. Much higher sea levels reported by Grant (1977) in the Atlantic Provinces and Gulf of St. Lawrence can possibly be assigned to this episode.

TRANSITION 5e/5d AND SUBSTAGES 5d-5a

At Sites 645 (Baffin Bay) and 647 (southern Labrador Sea), this transition corresponds to a drastic 1.5‰ increase in the ^{18}O content of planktonic foraminifers, not unlike that of the stage 5a/4 transition, whereas Site 646, off Greenland, shows a lesser shift toward heavier values. This and also the synchronous micropaleontological changes that are observed suggest a significant ice growth at least over eastern Arctic Canada, notably on Baffin Island as proposed by Andrews *et al.* (1972, 1984), and probably over Greenland (Funder, 1989). To account for such a large drop in $\delta^{18}O$ values, ice storage had to be important. Direct comparison of stage 5e/5d and 2/1 transitions is difficult since differences in the

TABLE I

Schematic outline of the last 130,000 years glacial/interglacial history in eastern Canada and adjacent basins.

Isotopic stages	Main Events		
1	Late settlement of full interglacial conditions in Arctic areas Diachronous "climatic optimum"		
2/1	Diachronous northward vegetational shifts Major and continuous phase of ice retreat after 11,000 BP Early meltwater transit phase shortly after 17,000 BP in western Labrador Sea		
2	Maximum Wisconsinan ice over eastern Canada Low salinity in the Labrador Sea surface water (ice meltwater) Low dinoflagellate productivity in neritic zones		
3	Episodic meltwater transit phases Limited resorption of the ice sheet(s) Boreal forest/tundra forest/tundra along the SE ice margin		
4	Abrupt and short ice stadial (~5000 yrs) Laurentide ice inception in St. Lawrence Lowlands (~80,000 yrs)		
5d to 5a	Early development (5d) of ice over Arctic Canada & Greenland	? ↑ ? Laurentide Ice inception over northern areas ? ↓ ?	Persistance of a cool/temperate climate over SE Atlantic Canada
5e	Full (warmest) interglacial conditions onshore and offshore Subarctic conditions in the Baffin Bay Significant retreat of Greenland ice Northernmost extension of deciduous forest in eastern Canada		
6/5e	Sharpest ^{18}O-shift in the record/fast ice melting Drastic vegetational transition in Atlantic Canada		
6	Maximum extension of the Laurentide Ice over Labrador & NS shelf Maximum ice storage (heaviest $\delta^{18}O$ values in the records)		

2. We do not know the isotopic composition of the Illinoian ice. Reconstruction of paleo-ice sheets from deep sea ^{18}O data remains purely speculative.

isotopic composition and spatial distribution of the corresponding ice covers certainly exist. It is however significant that the $\delta^{18}O$ values of substage 5d are higher than those of termination 1A (*cf.* Duplessy *et al.*, 1981). Inception of the Laurentide Ice Sheet during this episode should be considered a possibility.

Meanwhile, in southeastern Canada, the "warm" deciduous forest was replaced by a mixed forest, apparently still well spread during substage 5a, which indicates a slight cooling and wetter conditions. The age of its settlement is known by default ($\sim$85,000$<$t$<\sim$125,000 yrs) from the Th/U measurements discussed above.

STAGE 5A/4 TRANSITION

This transition corresponds to the earliest ascertained Early Wisconsinan extension of the Laurentide Ice Sheet that dammed the central St. Lawrence Lowland allowing Lake Deschaillons development. The latter cannot be younger than *ca.* 80,000 yrs (*cf.* Hillaire-Marcel and Causse, 1988a). This age and the brevity of isotopic stage 4 in all cores from the adjacent basins suggest that ice expansion over mainland eastern Canada was either very fast or that it began earlier during substages 5d to 5b. The spreading of Wisconsinan ice during stage 4, notably over southern Cape Breton Island, is still questionable. Palynological records indicate the replacement of the mixed forest of isotopic substage 5a by boreal forest/tundra-forest vegetational covers. However, we do not know the age of this vegetational change and cannot demonstrate the continuity of the records to which we refer.

STAGE 3

The Middle Wisconsinan episode is well recorded both offshore and onshore. Strong meltwater episodes are indicated by "light" peaks in all ^{18}O profiles from the Baffin Bay and Labrador Sea and correlative low salinity dinocyst assemblages (de Vernal and Hillaire-Marcel, 1986). They indicate phases of significant ice decay. One of them allowed partial deglaciation of the Appalachian foothills of Québec some 46,000 yrs ago, when Lake Gayhurst developed (*cf.* Hillaire-Marcel and Causse, 1988b) and possibly that of eastern Baffin Island (*cf.* Miller *et al.*, 1977; Brigham, 1983; Andrews and Miller, 1984). Fluctuation of the southern ice margin within the Great Lakes area is also shown by most stratigraphical sequences there (*e.g.* Dreimanis, 1977; Karrow, 1984). Meanwhile, ice-free conditions probably persisted over some littoral areas of the Atlantic Provinces, as shown by the well spread remains of palynostratigraphical unit III, although proximity of fluctuating ice margins is indicated by high relative sea levels observed notably at Castle Bay on Cape Breton Island.

^{14}C ages on planktonic foraminifers from some of our cores and ^{18}O correlations with reference records (*cf.* Martinson *et al.*, 1987) set a probably diachronous termination of this Middle Wisconsinan episode between *ca.* 32,000 (Shackleton and Opdyke, 1973), or slightly before (see core 76-029-033, Fig. 2A) in the Baffin Bay to *ca.* 30,000 BP, in the northern Gulf of St. Lawrence (Gratton *et al.*, 1986).

STAGE 2

Within all eastern Canadian Late Pleistocene records, the Late Wisconsinan ($\sim$ stage 2) corresponds to the most severe climatic conditions of the whole Late Pleistocene. They are shown by a maximum extension of the Laurentide Ice Sheet and its satellitic ice caps in the south and also by the extension of a dense sea ice cover over the margins of the Labrador Sea resulting in very low phytoplanktonic productivities (Aksu and Mudie, 1985; de Vernal and Hillaire-Marcel, 1977b). ^{18}O curves also show the highest values of the whole episode that are indicative of maximum ice storage. In the Labrador Sea, discrete meltwater inputs off the Laurentide and Greenland ice margins maintained relatively diluted surface water masses as shown by the ^{18}O and dinocyst records on the Labrador and Greenland rises. It is also notable that dinocyst productivity, although low in the Labrador Sea, is 1 to 2 orders of magnitude higher than under permanent pack ice of the Arctic Ocean (Mudie, 1985; Aksu *et al.*, 1988).

TRANSITION 2/1

We will not expand on the ice retreat in eastern Canada since it is already documented by several studies and presented in several review papers (*e.g.* Hillaire-Marcel and Occhietti, 1980). We will however mention some conclusions that can be drawn from the high-resolution of the stage 2/1 transition that is provided by core 84-030-021 (Fig. 2D) off the Labrador coast. At *ca.* 17,000 BP, a strong meltwater episode is recorded in both the ^{18}O profile and dinocyst diagram. The isotopic event probably correlates with a late glacial drop in ^{18}O recorded in deep sea cores from lower latitudes (*e.g.* Kennett and Shackleton, 1975; Leventer *et al.*, 1982; Mix and Ruddiman, 1985; see also cores from our sites). However, in core 84-030-021, this event is marked by a much larger shift in $\delta^{18}O$ values (a difference of *ca.* one order of magnitud of magnitude). The attenuated response of the global ocean is probably due to the homogenization of the large meltwater input through the Labrador Current. This transit responded to a significant melting of the northeastern Laurentide ice margin and possibly of the Inuitian ice margins as early as *ca.* 17,000 BP. This melting event could account for the early deglaciation of high altitude areas of the Torngat Mountains (north Labrador; *cf.* Short, 1981; Somma, 1984).

Subsequent recurrence of high $\delta^{18}O$ values in this core indicates a "restabilized" ice sheet. The main ice retreat phase occurred finally after *ca.* 11,000 as shown by the final and continuous shift in ^{18}O.

This core and several others mentioned in this study or under examination by our research group, all of which originate from the Labrador Sea, Baffin Bay and Hudson Bay basins, seem to indicate a diachronous and relatively late attainment of full interglacial conditions during the Holocene (until *ca.* 4,000 BP). Paleoecological studies of postglacial marine fossil assemblages, notably by Andrews (1972) and Hillaire-Marcel (1979) already gave some evidence of this peculiarity of the high latitudinal basins. ^{14}C-measurements by AMS technique on several samples are in progress. They should soon make it possible to describe this pattern in more detail.

CONCLUSIONS

The deep sea cores examined in this paper provide an insight into the Late Quaternary paleoceanographical changes in the adjacent basins of eastern Canada. These basins were strongly influenced by the proximity of large continental ice masses. Meltwater transit episodes that resulted in the dilution of surface water masses are clearly recorded by the isotopic composition of planktonic formaninifers and also, with great sensitivity, by dinocyst assemblage changes. Moreover, the huge complex of the Laurentide Ice Sheet and satellitic ice caps induced significant changes in atmospheric circulation patterns that are partly recorded in the pollen content of deep sea cores. For example, catabatic winds at the glacier margins may have occasionally allowed considerable extension of the sea ice cover, in the Labrador Sea notably. Low phytoplanktonic productivities are seen during such episodes, particularly during the last ice maximum (stage 2). It has still to be demonstrated that such phases of sea ice expansion allowed the formation of cold and dense surface waters that, after sinking in the North Atlantic margin could have contributed to significant renewal of deep oceanic waters in conjunction with deep water from the Norwegian Sea (Labeyrie and Duplessy, 1987). Comparative ^{18}O-measurements on benthic foraminifers are needed to document this potential role of the Labrador Sea. More studies are also needed to investigate the role of these basins with respect to the origin and trajectories of atmospheric moisture allowing ice growth at high latitudes. When looking at the distribution of DSDP/ODP Sites in the World's oceans, we find a few spots at high latitudes of the Northern hemisphere (DSDP Legs 12, 19, 38, 94 and ODP Leg 104) and the first continuous coring in the Labrador Sea and the Baffin Bay was made during Leg 105. From the viewpoint of the last ice ages paleoclimatic history, more coring for high resolution studies is needed before firm conclusions can be set.

On land, we still face the difficulty of finding relatively continuous records, although too little attention has been paid to the potential of small marginal basins such as Lake Bras d'Or on Cape Breton Island, where some thick Late Pleistocene sedimentary sequences seem to be present. Moreover, when partial records are found, they often lack any "absolute" chronological control. Correlations are often based on paleogeographical inferences or on climatostratigraphic "compatibilities" of the compared sequences... with the inherent risk of these approaches. We have seen that recent palynological work in the Atlantic Provinces finally resulted in the setting of the broad lines of a palynostratigraphy for the last Interglacial that may already provide better grounds for correlation. It is however obvious that the third unit is still "floating" in time: boreal forest/tundra forest covers certainly existed in eastern and northern Canada for most of its "non glacial" history since the phasing of the glacial/interglacial cycles of the Quaternary. Tills and varves are not much better elements for lithostratigraphical correlations. We are finally left with a difficult task: that of setting absolute time marks in units are not really suitable for this. All methods should be called for: progress has been made in thermoluminescence dating combined with other methods (Lamothe and Huntley, 1988) and in the Th/U dating of "open systems" (Rosholt *et al.*, 1985; Hillaire-Marcel and Causse, 1989). More work is needed with aminoacid racemisation rates...and ahead of these efforts, we still have to complete, sometimes to revise, our stratigraphical records.

ACKNOWLEDGEMENTS

Thanks are due to Caroline Guilmette and Claire Goyette at the GEOTOP (UQAM) who respectively carried out oxygen isotope analyses and provided technical support for palynological studies of cores HU-75-37 and 87-033-008 (new sets of data). Michelle Laithier (Sciences de la Terre, UQAM) is responsible for the drawings. Very carefull reviews from Peta Mudie (Atlantic Geoscience Centre, Dartmouth) and Sven Funder (Geologisk Museum, Copenhagen) strongly helped to revised our manuscript. We acknowledge here their help. All contributions from the GEOTOP group that were mentioned in this paper have received financial support from NSERC-Canada and the Fonds FCAR of Québec.

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